Transactions of the American Fisheries Society 114:12–30, 1985

The Decline of Striped Bass in the Sacramento–San Joaquin Estuary, California

DONALD E. STEVENS, DAVID W. KOHLHORST, AND LEE W. MILLER

California Department of Fish and Game, Bay–Delta Fishery Project
Stockton, California 95205

D. W. KELLEY

D. W. Kelley and Associates, 8955 Langs Hill Road
Newcastle, California 95658

Abstract

The abundance of young striped bass *Morone saxatilis* in the Sacramento–San Joaquin Estuary has suffered an unsteady but persistent decline from population levels that were high in the middle 1960s. The decline was particularly severe in 1977 and abundance of young striped bass has been low every subsequent year. The adult striped bass population also has fallen during the past 20 years, but the exact period over which the decline occurred and the rate of decline are not clear. The adult population is now about one-quarter of its former size and there is little sign of recovery. We believe the Sacramento–San Joaquin striped bass population and the fishery that it supports are in serious danger. The cause is most likely one or more of four factors. (1) The adult population is now so low that egg production may be inadequate. (2) The plankton food supply of young striped bass in the western Sacramento–San Joaquin Delta and Suisun Bay has been greatly reduced each spring. Diversion of water from the delta for agricultural purposes is a prime suspect for the decrease in food production. (3) Large numbers of young fish are lost by entrainment in water diversions. (4) The population is stressed by toxic substances such as petrochemicals and pesticides. Additional studies are underway to help determine the principal cause(s) of the striped bass decline.

Striped bass *Morone saxatilis* were introduced into the Sacramento–San Joaquin Estuary in 1879. Their abundance increased dramatically, enabling sport and commercial fisheries to develop before 1900. The commercial fishery was closed in 1935 due to pressure from sport fishermen (Stevens 1980). The population has never been dominated by rare strong year classes and until recently has been relatively stable. Now, however, the adult population is one-quarter of what it was 20 years ago, and the production of young over the past 8 years has been one-third to one-half of the expected values. These meager year classes of young probably will further depress the adult stock as they are recruited into the fishery.

This paper summarizes current thinking regarding potential causes of the declines of both young and adult striped bass. The initial work was done by California Department of Fish and Game (CFG) staff in 1980–1981. The analysis was continued by the CFG staff and a "Striped Bass Working Group" of scientists organized by the State Water Resources Control Board in 1982 to review the potential causes and identify corrective action. Kelley chaired this group. Other members were Stevens; Kohlhorst; Miller; James F. Arthur, United States Bureau of Reclamation; Louis W. Botsford, University of California, Davis; Thomas C. Cannon, Envirosphere; Gerald C. Cox and Richard M. Sitts, California Department of Water Resources (Sitts now is with Envirosphere); Stephen R. Hansen and Charles H. Hanson, Ecological Analysts (Hanson now is with Tera); Martin A. Kjelson, United States Fish and Wildlife Service; Jerry L. Turner, D. W. Kelley and Associates; and Roger S. C. Wolcott, Jr., and Thomas G. Yocom, National Marine Fisheries Service.

The Estuary

The Sacramento–San Joaquin Estuary begins where the Sacramento and San Joaquin rivers join to form the Sacramento–San Joaquin Delta (Fig. 1). It embraces the salinity gradient, which extends about 80 km from the western delta to San Pablo Bay and sometimes to San Francisco Bay. Freshwater outflows often range from a winter or spring high of 1,500–4,500 m^3/second to summer lows around 100 m^3/second released

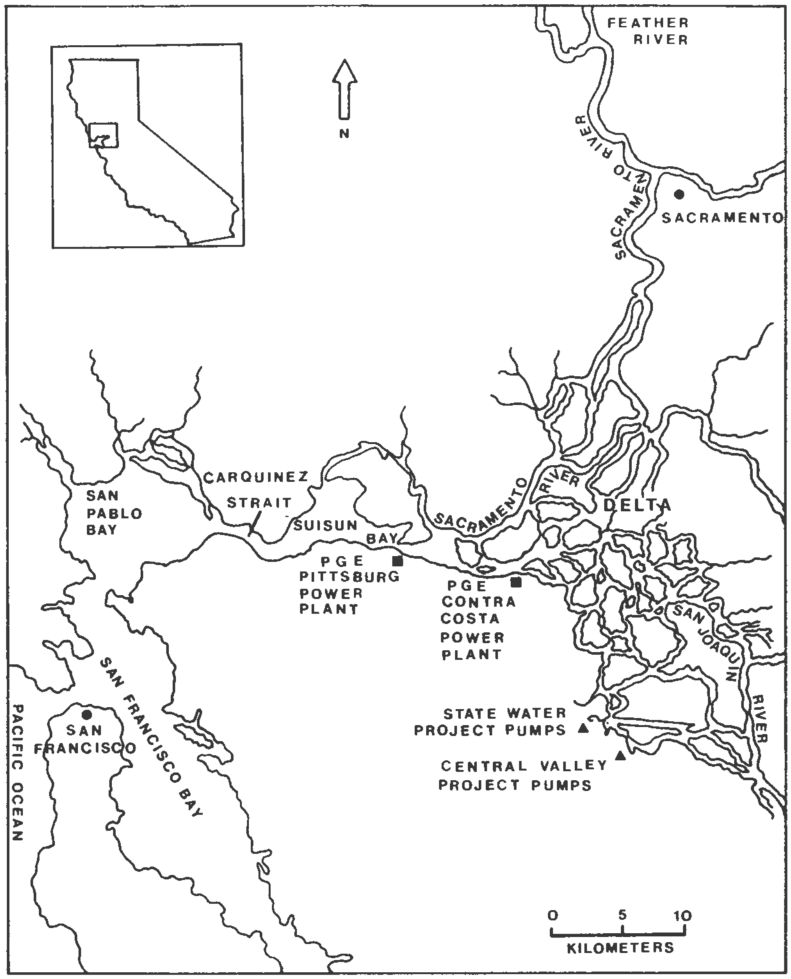


FIGURE 1.—*Sacramento–San Joaquin River system. The principal striped bass nursery areas are the broad channels of the western delta and Suisun Bay.*

from upstream reservoirs to keep salinity out of the delta and to protect fish. The historical average freshwater outflow to the ocean of about 1,100 m^3/second has been reduced by about one-half as a result of consumptive uses upstream and diversions from the delta (Chadwick 1977).

As in other estuaries, there is a zone at the upper end of the salinity gradient called the "critical zone" (Massmann 1963), "null zone" (Conomos and Peterson 1974), or "entrapment zone" (Arthur and Ball 1979), where the meeting of bottom saline water and surface fresh water produces vertical circulation cells and little net flow. Phytoplankton and zooplankton populations are often largest in this zone (Arthur and Ball 1979; Orsi and Knutson 1979) and its location is thought to be important to the young of many fishes, including striped bass (Massmann 1971; Turner and Chadwick 1972). The zone is farther downstream, usually in Suisun Bay, when freshwater outflows are high, and upstream in the western delta when the outflows are low. Plankton production is much greater when the zone is located in Suisun Bay, possibly because of the shallow tidal flats where the photic zone constitutes a greater percentage of the total depth than in the deep channels of the delta (Arthur and Ball 1979).

Sport Fishery

Striped bass is the major sport fish in the estuary. Striped bass anglers fish from the Pacific

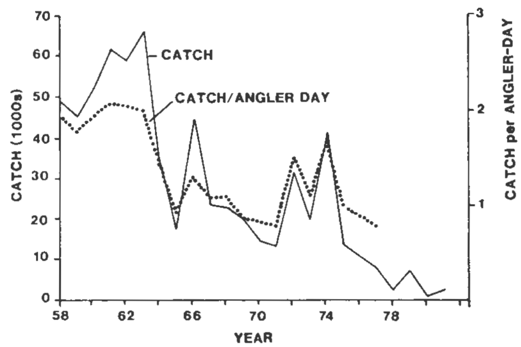


FIGURE 2.—*Trends in striped bass catch and catch per angler day reported by charter boats in the San Francisco Bay area.*

Ocean beaches near San Francisco upstream through the estuary into the Sacramento and San Joaquin rivers more than 200 km above the delta. Angling occurs the year around, but fishing localities vary seasonally in accordance with the striped bass migratory pattern. The fall migration of striped bass upstream from San Francisco Bay to the delta is marked by good fishing in San Pablo and Suisun bays. Fishing in the delta also improves gradually with the movement of striped bass into that area and then declines as the water temperature drops in winter.

Fishing success improves as the water warms in March. Those striped bass that have wintered in the bays start moving upstream to fresh water for spawning. During the spring, adults are spread through the delta and over 200 km north in the Sacramento and Feather rivers. Good fishing can be expected in the river spawning area at this time and occasional good catches are made in the bays.

By mid-June, most adult striped bass have left the delta and returned to brackish and salt water. During summer and early fall, fishing reaches its peak in Carquinez Strait, San Pablo Bay, and San Francisco Bay. Sometimes large numbers of striped bass migrate into the Pacific Ocean, where many are caught by surf-casters.

Most fishing is from shore and private boats, although charter boats are an important component of the fishery in the San Francisco–San Pablo Bay area. Charter boat operators are required to report catches to CFG. Although these boats generally have taken only 10–15% of the total catch and their fishing locations and methods have changed over the years, their reports are the best long-term striped bass catch records available (Stevens 1977a). From 1958 to 1980, the reported annual catch by charter boats declined from 48,900 to 1,400 striped bass (Fig. 2). Catches have been particularly low since 1976. The catch per angler-day on charter boats is available from 1958 to 1977. It decreased from 1.96 to 0.78 fish during this period, although the general downward trend in the fishery was interrupted by good fishing in 1966, 1972, and 1974.

Total catches on charter boats are affected by the number of anglers willing to pay for a day's fishing. Not surprisingly, fishing effort varies according to angler success (Miller 1974). Thus, low success has caused effort to drop off sharply in recent years, which probably has caused total catch on charter boats to decline more severely than the catch for the striped bass fishery as a whole. Nevertheless, our observations of the fishery have convinced us that the overall catch trend truly is downward.

Concern about the striped bass fishery resulted in a change in angling regulations in 1982. Now the minimum total length is 45.7 cm and the daily bag limit is two fish. From 1956 to 1981, the minimum length was 40.6 cm and the bag limit was three fish. Earlier regulations were more liberal: usually a 30.5-cm minimum length and a five-fish bag.

Decline of the Adult Striped Bass Population

The California Department of Fish and Game has measured adult striped bass abundance with Petersen population estimates and the catch per effort (CPE) of adult striped bass (total length ≥ 40.6 cm) captured during tagging studies. Modified Petersen mark–recapture population estimates (Bailey 1951) were calculated annually from 1969 through 1982. Striped bass were tagged with disc dangler tags (Chadwick 1963) during their spring spawning migration to the delta and Sacramento River. The ratio of tagged to untagged fish in the population was estimated during annual summer–fall creel censuses in the San Francisco Bay area and subsequent spring tagging operations.

The abundance estimation procedures are complicated by sex- and age-sampling biases (Chadwick 1967; Stevens 1977b). Hence, all of the abundance estimates are based on samples stratified by sex and age (Stevens 1977b). Variances for the stratified sex and age estimates were

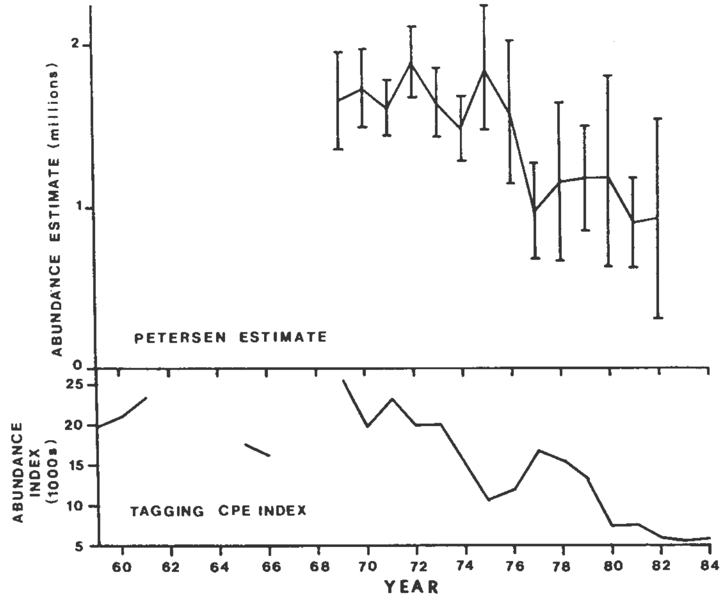


FIGURE 3.—*Trends in abundance of adult striped bass (≥40.6 cm total length) in the Sacramento–San Joaquin Estuary. Vertical bars for the Petersen estimates are 95% confidence intervals. CPE is catch per effort.*

calculated with Bailey's (1952) equation (4). These were summed to obtain the variance of the total population estimate for calculation of confidence intervals.

Sex was determined during spring tagging by applying external pressure to the abdomen of each fish. If milt was extruded, the fish was classified as male; otherwise it was classified as female. During the summer–fall creel census, sex was determined by dissection.

Age was determined from scales collected midway between the spinous dorsal fin and the lateral line. Scofield (1931) and Collins (1982) demonstrated that ages interpreted from California striped bass scales are valid.

According to the Petersen estimates, the striped bass population was remarkably stable between spring 1969, when the estimates began, and spring 1976 (Fig. 3). It then declined by about 40% and remained near this lower level through 1982.

Our second assessment of adult striped bass stocks is from catches of striped bass in CFG gill nets and fyke traps (Hallock et al. 1957) during tagging operations in the delta and Sacramento River. This CPE index is the sum of catches in the fishing gears after annual effort was standardized to four gill-netting boat-months and 36 fyke-trap-months. A boat-month is 20, 8-hour days of fishing a 183-m-long drift gill net (10.2–14.0 cm stretched mesh). A trap-month is 30, 24-hour days of fyke-trap fishing. In years when fishing occurred, effort ranged from 2 to 4.5 boat-months and from 11 to 42 trap-months.

Tagging began in 1958 (Chadwick 1968), but CPE records have been consistent only since 1959. Fyke traps were not fished in 1959–1961, 1965–1966, 1977–1978, or 1981. In those years, CPE indices were estimated by multiplying gill net catches by 1.61, the mean ratio of total catch to standardized gill net catch in 1969–1976 and 1979–1980. We did not include 1982–1984 in calculating the mean ratio because the ratio in those years was up to 2.3 times higher than in any previous year.

The CPE index indicates that the striped bass population declined steadily from the late 1960s to a low level in 1975. It then rose briefly, but declined to even lower levels by 1984 (Fig. 3).

There is no question that the population of adult striped bass in the estuary has fallen to a low level—much lower than when estimates were first available 20 years ago. However, the period over which the decline actually occurred and the rate of decline are not clear.

Adult Mortality Rate

Increased mortality helps account for the decline in adult striped bass abundance. Annual

TABLE 1.—*Number of tagged fish released, response rate, and mortality rates for striped bass age 5 and above in the Sacramento–San Joaquin Estuary.*

Year	Number released		Response rate[a]	Annual mortality rate	Exploitation rate	Expectation of natural death
	Males	Females				
1969	4,662	4,131	0.576	0.369	0.224	0.145
1970	1,585	1,889	0.551	0.395	0.148	0.247
1971	2,024	1,454	0.528	0.301	0.165	0.136
1972	4,002	4,407	0.504	0.407	0.185	0.222
1973	3,570	3,453	0.481	0.475	0.188	0.287
1974	2,710	3,035	0.460	0.399	0.241	0.158
1975	1,106	1,480	0.439	0.460	0.237	0.223
1976	2,008	1,741	0.419	0.456	0.269	0.187
1977	707	612	0.398	0.489	0.241	0.248

[a] Estimated fraction of recovered nonreward tags that anglers actually return. The estimation assumes all recovered $20 reward tags were returned. Because $20 tags were not released every year and response decreased over the years as catches of tagged fish became more common, we calculated linear regressions of return rate ratio on year for (1) nonreward : $5 tags, (2) $5 tags : $10 tags, and (3) $10 tags : $20 tags. Response for each year was estimated as the product of those three ratios taken from the regression lines.

mortality rate A was calculated as the complement of annual survival rate S (Ricker 1975) for striped bass age 5 and older. Younger fish were not fully vulnerable to CFG sampling and, because their mortality differs from that of older fish, they could not be included without inducing bias in the overall mortality estimates.

Survival rate was estimated from tag returns by the maximum-likelihood method of Brownie et al. (1978). This technique fits tag return data to specific models of survival and recovery rates and allows the investigator to choose the model that best fits the data. Their model H2 was the most appropriate model as determined by chi-square goodness-of-fit tests. Based on the distribution of tag returns, this model indicates that survival and recovery rates varied annually and that the reporting rate for newly released fish was different from that for survivors of releases in previous years.

Expectation of natural death was calculated by subtracting exploitation from total annual mortality. Exploitation rate u for ages 5 and greater was estimated from returns of nonreward tags corrected for incomplete reporting of tag recoveries by anglers:

$$u = \frac{R}{M};$$

R = number of tags recovered in the first year after tagging;

M = number of tags released at the beginning of the tag-return year.

We estimated response rate (fraction of recovered tags that anglers actually returned to us) annually by comparing return rates for nonreward tags with those for reward tags (Chadwick 1968). Reward tags with values of $5, $10, and $20 were used and we assumed all recovered $20 tags were returned. Corrections ranged from 0.398 to 0.576 (Table 1). Response corrections were applied only to voluntary returns by anglers through the mail. Tags observed during our summer–fall creel census in the San Francisco Bay area were assumed to be completely reported.

Estimated annual mortality of adult striped bass increased from less than 40% in 1969 to almost 50% in 1977. (Due to data processing delays, we do not have subsequent estimates.) Increased exploitation accounts for most of the increase in mortality after 1969; the greatest change occurred between 1970 and 1976 when the harvest increased from 15% to 27%. The positive trends in annual total mortality and exploitation from 1969 to 1977 were both statistically significant ($P < 0.05$). Most of the annual variability in total mortality apparently resulted from fluctuations in natural mortality which varied considerably from year to year but did not have a statistically significant trend.

Although the source of fishing mortality is obvious, the potential causes of natural mortality are more obscure and difficult to assess. The Striped Bass Working Group explored two potential sources of this natural mortality: toxic substances and an inadequate food supply.

Toxic substances and the health of striped bass from the Sacramento–San Joaquin system have

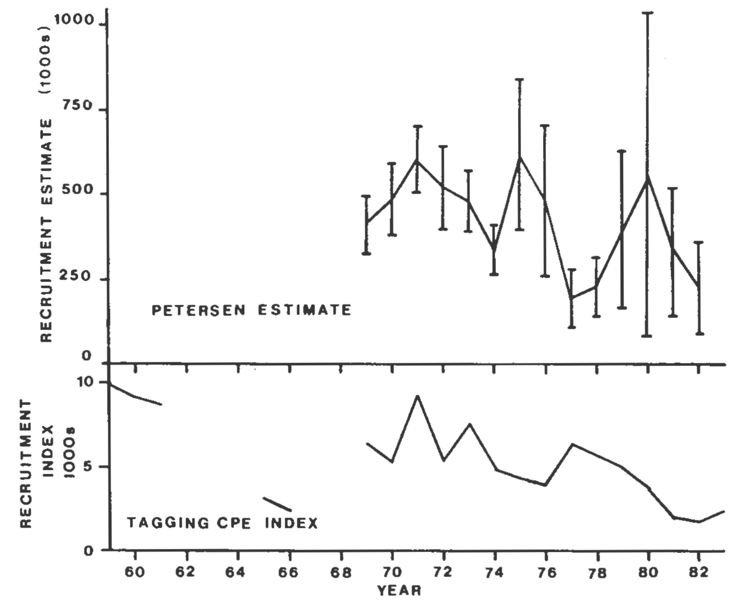


FIGURE 4.—*Trends in striped bass recruitment at age 4 in the Sacramento–San Joaquin Estuary. Vertical bars for the Petersen estimates are 95% confidence intervals. CPE is catch per effort.*

been studied since 1978 (Whipple et al. 1981). Whipple and her staff at the National Marine Fisheries Service's Tiburon laboratory found that gonads, liver, and muscles of adult striped bass accumulated toxic substances, primarily monocyclic aromatic hydrocarbons (MAH), chlorinated hydrocarbons, and heavy metals. They found significant inverse correlations between concentrations of MAH and zinc in striped bass and fish health as measured by liver, gonad, and egg condition. High tissue concentrations of MAH and zinc also were associated with greater parasite infestation. Although these results suggest that toxic substances could affect adult striped bass mortality, there is no direct evidence that they have. Indeed, general water quality conditions in the estuary have been much improved in recent years.

The food supply for adult striped bass in the estuary has not been well measured, but any food shortage long and severe enough to cause mortality should affect growth. Collins (1982) found that, although 1970 and later year classes averaged 2 cm smaller than the 1965 to 1969 year classes, the actual growth rates of adult fish had not changed. Instead, the size reduction was due to recent slower growth during the first year of life.

Reduction in Recruitment

Reduced recruitment of young to the adult population also helps explain the decrease in total striped bass abundance. Although age-4 striped bass are not fully vulnerable to CFG sampling, they represent the first age group that is fully recruited to the fishery; thus, we used measures of their abundance to index recruitment. Scales were not collected before 1969, so earlier age-4 indices were based on the abundance of 50–59-cm fork length fish (Collins 1982).

Petersen estimates indicate recruitment is highly variable with no strong trend, although 1980 was the only above-average year after 1976 (Fig. 4). The estimates were highest (over 550,000 fish) in 1971, 1975, and 1980, and lowest (below 250,000 fish) in 1977, 1978, and 1982. The CPE index of age-4 striped bass also suggests recruitment has been relatively low in recent years, the result of a long-term decline since at least the early 1970s and possibly since 1959 (Fig. 4).

Abundance of Young

If year-class strength is set early in life, the number of adult striped bass would be affected by the number of young surviving in prior years. To evaluate the importance of initial year class

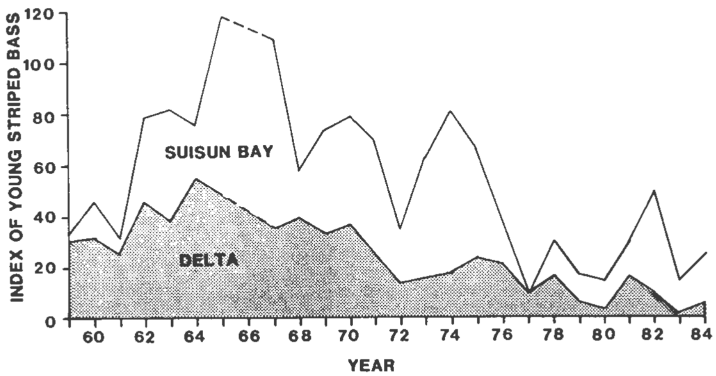


FIGURE 5.—*Annual index of young striped bass abundance by area in the Sacramento–San Joaquin Estuary. No sampling was conducted in 1966.*

strength, we calculated correlation coefficients between both of our measures of recruitment and the abundance of young 4 years earlier as measured by the CFG summer tow-net survey.

Recruit abundance measure	Year classes in correlation	Correlation with young of the year
Petersen age-4 estimate	1965–1978	0.19 (NS)
Tagging CPE age-4 index	1965–1979	0.85 ($P < 0.01$)

Both correlations indicate a positive association between recruitment and young striped bass abundance, but only the CPE correlation was statistically significant. Thus, these results are not definitive, but they do suggest that recruitment of a year class to the adult stock is affected by its abundance early in life.

Decline in Young-of-the-Year Production

Since 1959, CFG has sampled young-of-the-year striped bass every second week from late

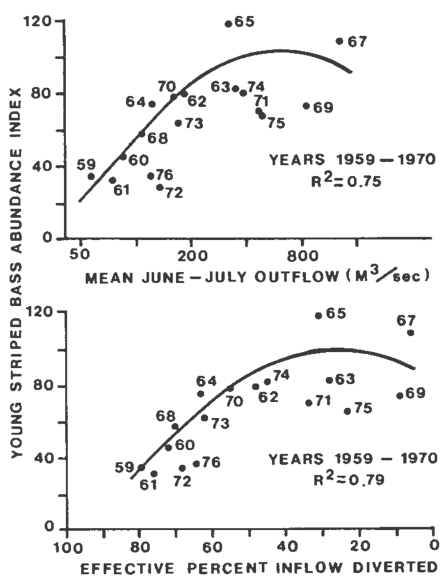


FIGURE 6.—*Relationship between total abundance of young striped bass in the Sacramento–San Joaquin Estuary and delta outflow and diversion. Curves are fits to 1959–1970 data.*

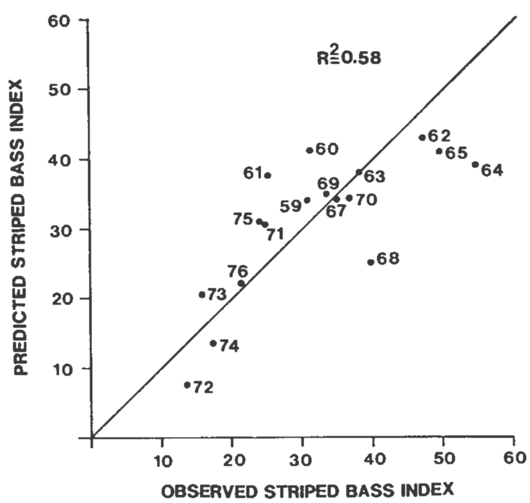


FIGURE 7.—*Relationship between actual and predicted striped bass abundance in the Sacramento–San Joaquin Delta. Predicted abundance = −170 − 0.196 (mean daily May–June water diversion rate by water projects and local agriculture) + 178($\log_{10}$mean daily May–June delta outflow) − 34.2($\log_{10}$mean daily May–June delta outflow)^2. All flows are in m^3/second.*

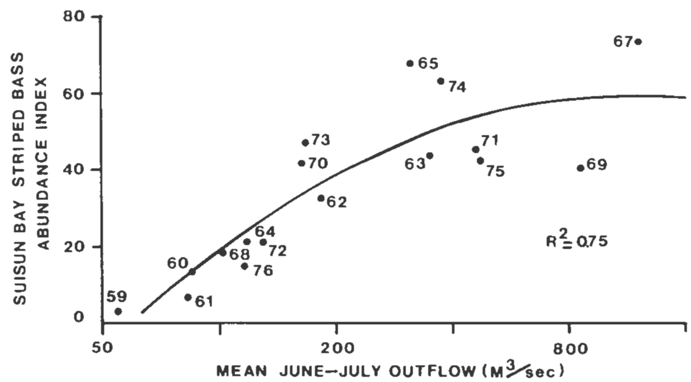


FIGURE 8.—*Relationship between young striped bass abundance in Suisun Bay and Sacramento–San Joaquin Delta outflow.*

June to late July or early August throughout the nursery habitat. The fish are measured and, when their mean fork length reaches 38 mm, a young-of-the-year index is calculated on the basis of catch per net tow and the volume of water in the areas where the fish are caught (Turner and Chadwick 1972).

The sampling for young striped bass occurs primarily in the delta and Suisun Bay. The young-of-the-year index has a well-recognized bias in high-flow years, when a larger proportion of the young is washed downstream into San Pablo Bay; the extremely large volume of water there is not sampled effectively. Hence, in very wet years, the index is an underestimate of the actual population (Stevens 1977a, 1977b).

This survey has revealed that abundance of young-of-the-year striped bass has been declining unevenly but persistently since high levels in the mid-1960s (Fig. 5). The decline has been most pronounced in the delta, but is clearly apparent in Suisun Bay despite greater year-to-year fluctuations there.

During the years 1959–1970, the abundance of young striped bass was highly correlated both positively with freshwater outflow from the delta and negatively with the percent of the river inflow diverted from the delta channels during spring and early summer by the federal Central Valley Project (CVP), the California State Water Project (SWP), and delta farmers (Fig. 6). Conditions during June and July provided the highest correlations. In years when outflow was high and the percent of river inflow diverted was low, the striped bass index was high; conversely, when outflows were low and the percent diverted was high, the young striped bass index was low (Turner and Chadwick 1972).

In the early 1970s, young striped bass abundance was lower than expected based on the 1959–1970 relationships with outflows and diversions. In the delta portion of the estuary, the decline was explained by increased diversion rates in May and June (Chadwick et al. 1977). Hence, for years 1959–1976, May and June outflows and the amount of water diverted in those months accounted for variations in young striped bass abundance in the delta (Fig. 7). Young striped bass abundance in Suisun Bay for those years was best explained by June–July outflow (Fig. 8). However, since 1977, the abundance of young striped bass has been considerably lower than predicted by the 1959–1976 regressions. Both juvenile striped bass abundance and our ability to predict it has been greatly reduced.

The Striped Bass Working Group reviewed several possible causes for the decline of young striped bass. They concluded that four remain as probable major contributors to the problem:

(1) the adult population, reduced by a combination of lower recruitment and higher mortality rates, produces fewer eggs;

(2) production of food for young striped bass has been reduced;

(3) large numbers of striped bass eggs and young are removed from the estuary by diversion with water needed for agriculture, power plant cooling, and other uses;

(4) point and nonpoint discharges of pesticides and other petroleum products may cause

TABLE 2.—*Fecundity of female striped bass in the Sacramento–San Joaquin Estuary.*

Age	Estimated eggs/ mature female (1,000s)	Maturity correction[a]	Estimated mean fecundity of females on spawning grounds (1,000s)	Migration correction[b]	Estimated mean fecundity of all females (1,000s)
4	243	0.35	85	0.16	14
5	447	0.87	389	0.90	350
6	652	1.00	652	1.00	652
7	856	1.00	856	1.00	856
≥8	1,427	1.00	1,427	1.00	1,427

[a] Fraction of female striped bass that are mature on the spawning grounds (Scofield 1931).
[b] Fraction of all female striped bass that migrate to the spawning grounds (from the female : male ratio in spring tagging from 1969 to 1978).

mortality of adults, reduce their ability to reproduce, or reduce the survival of their eggs and young.

Effect of Reduced Adult Stocks

We have hypothesized that the number of eggs being produced by the adult striped bass population has declined and that such a decline has contributed to the declining number of young.

To examine this hypothesis, we first calculated an annual index of egg production from our Petersen estimates and age-specific fecundity data. The abundance of each age class from age 4 to ages 8 and older combined were multiplied by the estimated fecundity for the appropriate age (Table 2). The annual index of total eggs spawned is the sum of these products.

We have calculated that egg production in 1982 was only about 25% of what it was during the late 1960s and early 1970s (Fig. 9). At first glance, a 75% reduction in egg production would seem an obvious reason for the striped bass decline. But with the average female striped bass producing nearly a half million eggs, it is hard for some biologists to envision there not being a surplus of eggs. This is because we are accustomed to believing that if fewer are produced, a greater proportion will survive to maintain the population. There is evidence to suggest that this "density-dependent" survival principle does not presently apply to the Sacramento–San Joaquin striped bass population.

We calculated a survival index between the egg and 38-mm stage for years (1969–1982) when egg production estimates were available,

$$\text{survival index} = \frac{\text{index of abundance when mean length is 38 mm}}{\text{egg production index}},$$

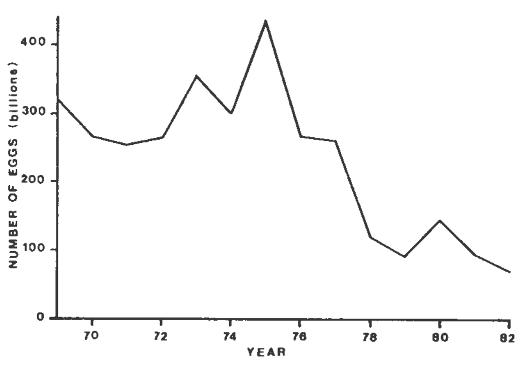


FIGURE 9.—*Trend in striped bass egg production in the Sacramento–San Joaquin Estuary.*

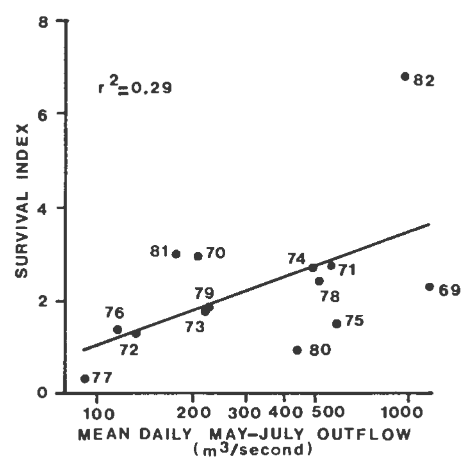


FIGURE 10.—*Striped bass survival index between the egg and 38-mm stages in relation to mean daily May–July freshwater outflow from the Sacramento–San Joaquin Delta. Survival = 2.39 $\log_{10}$ outflow − 3.70. Numbers next to points designate years.*

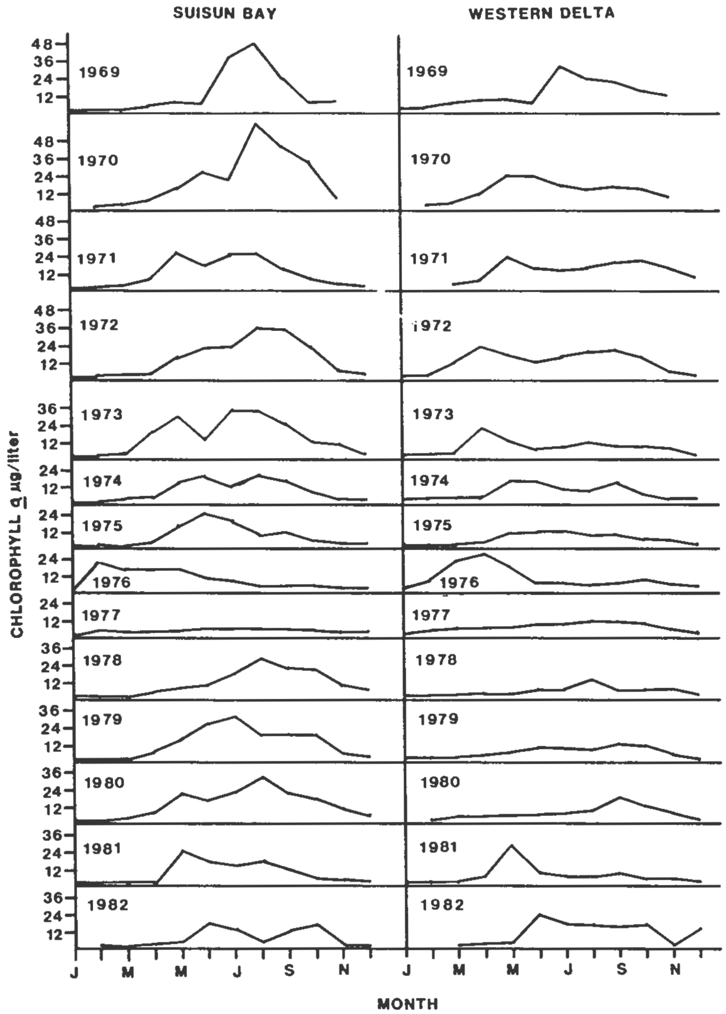


FIGURE 11.—*Mean chlorophyll-*a *concentrations in Suisun Bay and the western Sacramento–San Joaquin Delta.*

and regressed this survival index on $\log_{10}$(mean daily May–July outflow). This regression is statistically significant ($P < 0.05$), but it only accounts for 29% of the variation in survival (Fig. 10). These results, however, are affected by imprecision in the variables used to calculate the survival index. This imprecision is especially large in the Petersen estimates (Fig. 3).

Early work indicated that *abundance* of young striped bass in the summer was correlated with river flow suggesting that *survival* from eggs to the young-of-the-year stage could depend on flows and diversions (Turner and Chadwick 1972; Chadwick et al. 1977; Stevens 1977a). Our current analysis implies that the relationship between survival from egg to the 38-mm stage and flow has not changed substantially. Survival rates still appear to be controlled by delta outflow. The low egg production since 1976 has not resulted in higher survival rates. Hence, if the same relationship between survival and flow continued after 1976, a decline in egg production would have caused the young striped bass population to decline.

Reduced Food Production

In the Sacramento–San Joaquin Estuary, young striped bass begin feeding on small crustacean zooplankton a few days after they hatch (Eldridge

TABLE 3.—*Mean concentrations (numbers/m³) of food organisms utilized by young striped bass for different areas of the Sacramento–San Joaquin Estuary.*

Year	Western delta: Crustacean zooplankton[a]	Western delta: *Neomysis mercedis* >4 mm[a]	Suisun Bay: Crustacean zooplankton[a]	Suisun Bay: *Neomysis mercedis* >4 mm[a]	Location of striped bass larvae: crustacean zooplankton[b]
1968		125.1		54.2	
1969		64.1		61.1	
1970		26.0		38.1	
1971		28.4		41.5	
1972	56,260	51.6	96,130	28.9	107,220
1973	32,210	44.9	81,550	86.6	83,350
1974	24,560	34.1	55,920	77.0	86,470
1975	13,130	17.7	38,450	54.9	86,220
1976	21,510	33.4	30,770	35.9	54,050
1977	73,620	16.0	55,700	0.8	38,850
1978	11,310	17.6	49,070	34.8	16,110
1979	10,230	15.3	45,010	25.5	29,370
1980		31.1		60.3	
1981		26.5		20.1	
1982		12.6		45.3	
1983		2.9		14.6	

[a] Mean concentration from April through June.

[b] Mean concentration where and when young striped bass are first feeding.

et al. 1982). As they grow, they feed on larger zooplankters such as the opossum shrimp *Neomysis mercedis* (Heubach et al. 1963).

Information collected by CFG, the California Department of Water Resources, and the United States Bureau of Reclamation enabled the Striped Bass Working Group to evaluate trends in productivity of the nursery area during recent years. Phytoplankton are monitored by chlorophyll-*a* measurements. The largest crustacean zooplankton are sampled by 10-minute oblique tows from bottom to surface with a 154-μm-mesh Clark-Bumpus net. Pumps are used to sample zooplankton that pass through a 154-μm-mesh screen. Opossum shrimp are captured in 10-minute tows with a conical plankton net (Knutson and Orsi 1983). Generally, all plankton categories have been sampled at more than 30 locations at least twice monthly during the striped bass spawning and nursery period.

Phytoplankton monitoring data were available for this analysis from 1969 to 1982, crustacean zooplankton data from 1972 to 1979, and opossum shrimp data from 1968 to 1983. Although more recent plankton data have been collected, they are not yet available for analysis.

The data provide evidence of a general overall decline in the productivity of the striped bass nursery area during recent years. The decline has been great enough to cause a major reduction in the amount of food available for young striped bass.

In the western delta, upstream from the junction of the two rivers, there was a prominent spring bloom of phytoplankton each year until 1977, except for 1969 and 1975 (Fig. 11). No spring bloom occurred from 1977 to 1980. Blooms did occur briefly in May 1981 and in June 1982.

In Suisun Bay, an area with generally high biological productivity due to the presence of the entrapment zone in the spring and summer, we have learned to expect a small phytoplankton bloom in spring followed by a larger bloom in late summer. However, for almost 2 years, from summer 1976 to summer 1978, there was no bloom in Suisun Bay. Since 1978, Suisun Bay phytoplankton populations have recovered substantially.

Variations in zooplankton density exhibited a different pattern from those in phytoplankton. Average concentrations of crustacean zooplankton were very high in the western delta in 1977 (Table 3), apparently due to low freshwater flows associated with a drought in 1976 and 1977 that allowed the entrapment zone to encroach upstream. In that region, average zooplankton densities were at their lowest levels in 1978 and 1979, the last years for which data are available. There was not a distinct decline in the average abundance of crustacean zooplankton in Suisun Bay after 1977, although their average concentration did decline each year from 1972 to 1976 and concentrations from 1977 to 1979 were lower than the average of the previous years.

Because the average spring zooplankton concentrations did not clearly decline, the Striped Bass Working Group also examined the trend in abundance of zooplankton restricted to the times when young striped bass began feeding and the geographical region where young striped bass were located when they began feeding. If food availability is critical to striped bass survival, conditions experienced by the initial feeding stages are likely to have the greatest impact on year-class strength. The region where young striped bass were centered when they began to feed varied annually depending on the amount of fresh water flowing through the estuary (Table 4). In the drier years, virtually all of the striped bass were in the delta. As flows increased, the young striped bass began entering Suisun Bay and, in the wettest years, most were in Suisun Bay. In 3 years (1974, 1978, 1979) information on young striped bass distribution was not available so it was estimated from the relationship between striped bass distribution and flow in years when data were available. The zooplankton abundance indices derived from this more restrictive analysis exhibited a much more striking decline than was evident from the average spring concentrations (Table 3).

In the western delta, opossum shrimp abundance was very low in the spring from 1977 to 1979, moderate in 1980 and 1981, and low again in 1982 and 1983. In Suisun Bay, the *Neomysis* population was near zero in 1977. After that spring, there were moderate populations of *Neomysis* in the normal- to high-flow years 1978, 1980, and 1982, but their abundance was low in the low-flow years 1979 and 1981 and the high-flow year 1983.

We believe that these plankton data reflect a widespread and major reduction in biological productivity of the western delta and Suisun Bay during and following the 1976–1977 drought. There is evidence of recovery in Suisun Bay, but generally not in the western delta. What has caused this change?

Biologists have long been aware that phytoplankton, zooplankton, *Neomysis*, and other striped bass food organisms in the delta are influenced by the quantity of flows of the Sacramento and San Joaquin rivers, the location of the entrapment zone, and also the growing use of the delta channels as conduits to carry water south to the export pumps of the CVP and the SWP (Turner 1966; Turner and Heubach 1966; Heubach 1969; Arthur and Ball 1979; Knutson and Orsi 1983). More than a decade ago, investigations in the delta provided good evidence that increasing net velocities through the channels of the interior delta would lower zooplankton and *Neomysis* populations. The broad, and often deep, channels of the western delta seemed not as vulnerable.

TABLE 4.—*Distribution of first-feeding striped bass larvae in relation to river flow passing through the Sacramento–San Joaquin Estuary in May. ND means not determined.*

Year	Location of larvae	May outflow (m^3/second)
1977	Delta	114
1976	Delta	115
1972	Delta	146
1968	Delta	191
1970	Delta	305
1973	Delta and Suisun Bay	331
1979	ND	379
1974	ND	723
1971	Delta and Suisun Bay	748
1975	Delta and Suisun Bay	816
1978	ND	1,156
1969	Suisun Bay	1,828
1967	West Suisun Bay	2,111

Because phytoplankton is at the base of food chains and should respond rapidly to environmental changes, we searched for reasons why it has been less abundant in recent years. Jerry Turner of the Striped Bass Working Group observed that only two notable spring blooms have occurred in the western delta since 1976, and both immediately followed shutdowns of the SWP diversion pumps for repairs (Fig. 12). The first incident was in May 1981 when the first samples following the pump shutdown indicated that a significant phytoplankton bloom had suddenly developed. The second incident of this kind occurred early in June 1982 when the SWP pumps again were shut down for repair work and a major phytoplankton bloom followed.

These results suggest that the water project diversions are, in some as yet unexplained way, having a major effect on the phytoplankton population and basic productivity of the western delta. The most apparent mechanism is that the residence time of water increases in the channels

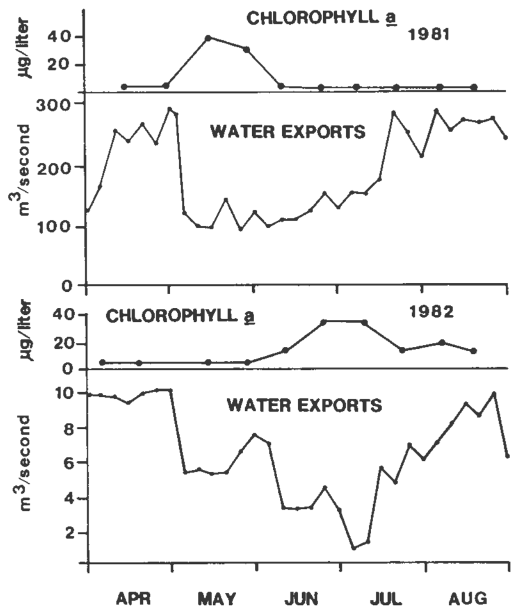


FIGURE 12.—*Trends in mean chlorophyll-*a *concentrations in the western Sacramento–San Joaquin Delta and water export rates at the federal Central Valley Project and State Water Project pumps from April to August 1981 and 1982. Note that phytoplankton blooms follow reductions in water export pumping.*

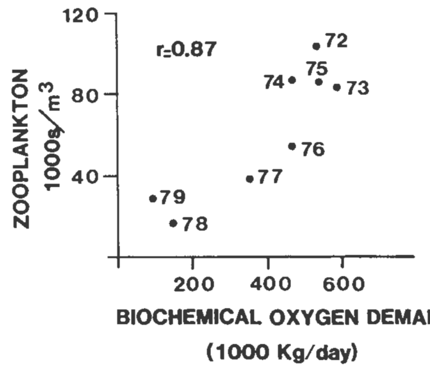


FIGURE 13.—*Relationship between zooplankton concentration at the time and place of initial striped bass feeding and an index of organic loading from point-source discharges in Suisun Bay and the western Sacramento–San Joaquin Delta.*

affected by the diversions when the pumps stop. However, attempts by ourselves and others to correlate the occurrence of spring phytoplankton blooms with more direct, although imperfect, measures of residence time have not provided conclusive results.

An alternative hypothesis to explain the reduced plankton populations was offered by Striped Bass Working Group member Charles Hanson. Inorganic nutrient concentrations have not fallen, but Hanson hypothesized that improved waste treatment at point-source discharges in the estuary during the first half of the 1970s has reduced the contribution of organic material to the system and may have contributed to a decline in the productivity of Suisun Bay and the delta, particularly in the production of microorganisms that are eaten by zooplankton. The abundance of zooplankton at the times and places where larval striped bass are concentrated is well correlated with Hanson's index of organic loading based on biochemical oxygen demand (BOD) data from six point-source discharges in Suisun Bay and the western delta (Fig. 13). In a multiple-regression analysis, the combination of May outflow and Hanson's index of organic loading in Suisun Bay and the western delta accounted for 80% of the variability in the striped bass index over the past decade.

These results suggest that changes in waste treatment may have contributed to reduced production of zooplankton and striped bass in the estuary and may be important in the striped bass decline. The Striped Bass Working Group concluded that this hypothesis is worthy of more detailed examination. That examination will require more careful assessment of organic input to the system from all sources, probably based on some measure other than BOD. Use of BOD as a measure of the value of organic detritus as an energy source to the ecosystem probably exaggerates the contribution of wastewater discharge.

Effect of Reduced Food on Young Striped Bass

Whatever the reason, phytoplankton and *Neomysis* populations have been low in both Suisun Bay and the western delta during most years since 1976. Although trends in average zooplankton abundance are less striking, the abundance of zooplankton when and where larval striped bass begin feeding clearly has declined since 1971. How important is this decline in productivity to striped bass?

Larval striped bass begin feeding on small crustacean zooplankters when the fish are 4–7 mm long (Eldridge et al. 1982). As these larval fish grow, they eat more and larger organisms. Laboratory studies have shown that larval fish

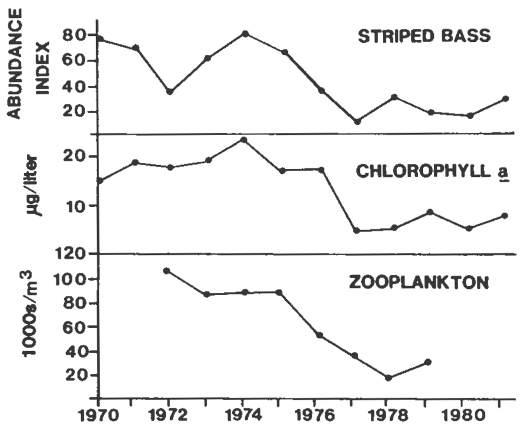


FIGURE 14.—*Concentration of chlorophyll* a *and zooplankton at the time and place of initial feeding by young striped bass (Table 4) compared with striped bass abundance in midsummer in the Sacramento–San Joaquin Estuary.*

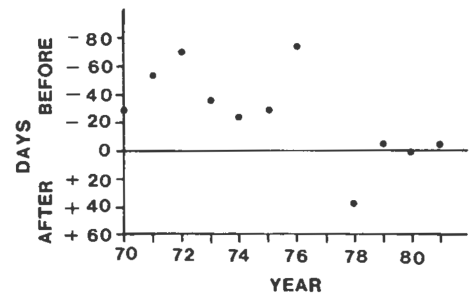


FIGURE 15.—*Number of days prior to or after initial feeding of larval striped bass that chlorophyll-*a *concentrations reached 10 µg/liter in the area of the Sacramento–San Joaquin Estuary where most striped bass larvae were located (Table 4).*

survival is directly related to the number of food organisms available to them (Daniel 1976; Miller 1978; Eldridge et al. 1981) and that high survival requires localized concentrations of food greater than are found in average field measures in the Sacramento–San Joaquin striped bass nursery area (Daniel 1976). The only fish that survive may be those that find themselves in dense patches of zooplankton. We compared the summer striped bass abundance index with phytoplankton and zooplankton densities 60 days earlier in the region where most striped bass began feeding. Since 1976, there has been very little phytoplankton or zooplankton where striped bass need it when they begin feeding (Fig. 14).

Striped Bass Working Group member Jerry Turner also found evidence that plankton population development has been delayed in recent years. Prior to 1977, chlorophyll-*a* concentrations where most of the striped bass began feeding reached 10 µg/liter from 3 to 10 weeks before the estimated date that young striped bass began feeding (Fig. 15). This should be a long enough period for high zooplankton populations to develop from feeding on the phytoplankton (Riley 1947). In 1977, chlorophyll-*a* concentrations in the delta never reached 10 µg/liter, and from 1978 to 1981, phytoplankton development where most young striped bass first began feeding, whether in the delta or in Suisun Bay, was delayed beyond the time that it was needed by the larval fish.

A comparison of mean chlorophyll-*a* concentrations in the western delta and Suisun Bay in April and May suggests that, in some years, the very early phytoplankton blooms in Suisun Bay may partially depend on phytoplankton being washed downstream from the western delta. As an example, note the May 1981 bloom in both the western delta and Suisun Bay (Fig. 11). The low concentrations of phytoplankton in the western delta since 1977 may be responsible for the lack of an early April–May peak in Suisun Bay, and would explain the delayed phytoplankton development where the young striped bass first begin feeding, whether in the western delta or Suisun Bay.

Entrainment Losses

Striped bass eggs, larvae, and juveniles are lost via entrainment in diversions of delta water by the CVP, the SWP, delta agriculture (DA), and the Pacific Gas and Electric Company (PGE). Fish losses depend on the density of organisms at the pump intakes, the pumping rate, and (in the case of PGE) mortality occurring during passage through the power plants before the cooling water is discharged back into the delta. Losses of striped bass have been estimated for power plants based on sampling within the cooling systems. Similar estimates of striped bass losses in CVP, SWP, or DA diversions are precluded by inadequate sampling. However, indirect estimates of these losses have been made by Richard Sitts of the Striped Bass Working Group (CVP, SWP), Alan Baracco of CFG (CVP, SWP), and Randall Brown of the California Department of Water Resources (DA). These estimates were de-

TABLE 5.—*Estimates of losses (in millions) of young striped bass to entrainment, Sacramento–San Joaquin Estuary. ND means not determined.*

Year	Central Valley Project and State Water Project pumps[a]	Delta agriculture[b]	Pacific Gas and Electric Company[c]
1968	1,878	ND	ND
1969	2	ND	ND
1970	1,784	ND	ND
1971	778	ND	ND
1972	4,527	ND	ND
1973	2,253	ND	ND
1974	ND	ND	ND
1975	234	ND	ND
1976	507	ND	ND
1977	249	ND	ND
1978	117	598	154
1979	286	562	62

[a] Estimates from 1968 to 1977 by A. Baracco, California Department of Fish and Game. Estimates for 1978 and 1979 by R. Sitts, Envirosphere Company and C. Hanson, Tera Corporation.

[b] Estimates by R. Brown, California Department of Water Resources.

[c] Estimates from 316b demonstrations for Contra Costa and Pittsburg power plants.

rived by multiplying estimates of striped bass egg and larva densities in the delta channels within the influence of the diversions by the amounts of water being diverted. The sampling of eggs and larvae is based on oblique tows with large plankton nets by CFG and PGE (Miller 1977; Stevens 1977b; PGE 1981a, 1981b). Baracco's estimates for the CVP and SWP are available from 1968 to 1977, CFG's striped bass egg and larva survey years. Sitts' estimates for the CVP and SWP, Brown's estimates for DA, and the estimates of losses at PGE power plants are available for 1978 and 1979.

Except for the PGE power plant estimates, these various entrainment-loss estimates are only gross approximations. They are subject to untested assumptions regarding sampling efficiencies, mortality occurring between the locations that were sampled and the diversion sites, and flow patterns in the delta channels. Yet the estimates, which range from millions to billions of fish, have convinced us that large numbers of small striped bass are lost from the estuarine population in many years (Table 5).

The evidence that survival from the egg to the 38-mm stage is independent of the striped bass population size suggests that the abundance of young striped bass surviving to midsummer is reduced by the large losses from the combined entrainment at the PGE plants, CVP and SWP pumps, and DA diversions. In turn, this long-term reduction in young striped bass abundance probably has contributed to the decline in the adult striped bass population.

TABLE 6.—*Irrigation return water as a percent of total Sacramento River flow.*

Month	1972	1973	1975	1976	1977	1980	1981
April	8.0	7.7		6.8	4.7	8.2	12.8
May	20.0	12.7	7.6	13.5	15.2	22.2	16.4
June	9.6	11.6	8.6	13.1	4.9	10.0	13.4
July	7.4	9.9	11.1	8.0	2.8	10.9	

Toxic Wastes

The hypothesis that survival of young striped bass has been reduced due to increased toxicity of the environment is virtually impossible to test because the toxicity data base is inadequate. Although most of the major waste treatment facilities discharging into the bay and delta have been much improved in the last decade, large quantities of potentially toxic substances still reach the system, and many are not routinely monitored. Much of the watersheds of the Sacramento and San Joaquin rivers are treated with pesticides each year, and although records of pesticide use are available, most are not monitored in streams. A variety of unmonitored toxicants also potentially enter the rivers and bays with runoff from industrial and urban areas whenever it rains, and, of course, accidental spills of all sorts commonly occur.

Thus, our analysis of this hypothesis is rather qualitative. The Striped Bass Working Group searched for indirect evidence of potential toxicity problems in streamflow records during the spawning season. These records allowed us to examine the fraction of the Sacramento River flow formed by irrigation return water potentially laden with pesticides. We believed that this approach could provide some insight because in the spring most irrigation water in the Sacramento River basin goes to rice farming. In general, water is diverted from the river or from reservoirs through irrigation canals, fields are flooded, pesticides are applied, and eventually the water is drained into sloughs and subsequently flows back into the river. Major irrigation drains discharge into the river in regions where striped bass eggs and larvae are found in high densities.

We also searched water quality monitoring data and other sources for records of fish kills and concentrations of toxicants known to be harmful to fish.

From streamflow records, Striped Bass Working Group member Stephen Hansen estimated that the five major sources of return irrigation water contribute between 5% and 20% of the total Sacramento River flow at or near Sacramento during April–July (Table 6). Pesticides and herbicides used in rice culture (molinate, chlorophenoxy acetic acid, ethyl parathion, methyl parathion, thiobencarb) are applied extensively during these months. Also of concern are toxaphene and xylene (a common pesticide solvent), which are not used specifically on rice but are extensively applied elsewhere. Detectable concentrations of several of these pesticides have been found in the Sacramento River and its tributaries during this period (Finlayson et al. 1982).

Measured concentrations of molinate found have been as high as 300 μg/liter, a level toxic to fish (Finlayson and Lew 1983), but those of the other pesticides have generally been at sublethal levels. Yet spring kills of resident fishes (cyprinids, centrarchids, ictalurids) in irrigation discharge drains of the Sacramento Basin and in the Sacramento River itself are frequent and usually associated with pesticides. Recent, as yet unpublished, toxicity tests by CFG (B. Finlayson) reveal that young striped bass are more sensitive to molinate and thiobencarb than are the resident fishes. Striped bass eggs and larvae also may suffer chronic effects from concentrations below lethal levels. Thus, the evidence that we have seen suggests that toxic substances may be damaging the health of striped bass, but it is not possible to determine the degree to which they are responsible for the striped bass decline.

Summary and Discussion

The adult striped bass population of the Sacramento–San Joaquin Estuary has fallen to the lowest levels since stock assessments were first available; it probably has dropped to the lowest levels since its early development after the 1879 introduction from the east coast. Angler catches and catch per unit of effort have unsteadily but persistently declined, and angler harvest increased from about 15% of the population in 1970 to about 27% in 1976. Despite this increase, exploitation is still lower than for Atlantic coast stocks (Kohlenstein 1981) that are fished commercially. However, population studies reveal that mortality is exceeding recruitment and until the cause of the decline is found and corrected, there may be a need for more fishing restrictions.

The principal reason for low recruitment to the adult population appears to be poor production of young of the year. Extensive summer townet surveys have provided good evidence that less than one-half as many young of the year are produced now as were produced a decade ago. The Striped Bass Working Group of scientists, appointed by the State Water Resources Control Board to analyze the problem, concluded that the decline was probably the result of a combination of (1) reduced adult stock producing fewer eggs, (2) reduced food production in the nursery area, (3) entrainment losses into water diversions, and (4) toxicity.

The decline in adult striped bass abundance has resulted in a 75% decline in egg production since the early 1970s. Our analysis suggests that egg production now may be inadequate to maintain the population at former levels under present environmental conditions, even though billions of eggs are still produced each year.

Food production in the striped bass nursery area has been reduced substantially in recent years. Phytoplankton populations in the salinity gradient have been very low. In spring, blooms thought necessary to provide zooplankton production for young striped bass have been either eliminated or delayed beyond the time when most of these fish begin feeding. There is evidence suggesting that phytoplankton development has been suppressed by the use of the major delta channels as conduits to carry increasing amounts of water to diversions in the south delta. Experiments to learn more about this are underway.

Entrainment losses of striped bass eggs, larvae, and young in water diversions are very high and may be important. In recent years, survival rates have depended upon freshwater outflow in the spring and early summer, just as they did before the decline. High outflows in recent years have not, however, resulted in high striped bass populations as they previously did. Hence, reduced egg production due to lower adult populations has not resulted in a density-dependent increase in survival rates between egg and young of the year, and any losses of early life stages, including losses due to entrainment, could be contributing to the problem.

The effect of toxicity has been one of the most difficult to assess. Obvious water pollution has been greatly reduced in recent years by major campaigns and expenditures to improve waste treatment. Nevertheless, there is evidence that toxic petrochemicals and trace metals may be present in concentrations sufficient to affect the health of both adult and juvenile striped bass.

The striped bass situation in the Sacramento–San Joaquin Estuary parallels the loss of many so-called "renewable" natural resources. Several factors are identified as probable causes; some may combine in their effects. One such combination that we find very plausible for the striped bass decline is the reduced number of eggs and larvae that now drift downstream to enter the nursery habitat and the recent lower production of planktonic food organisms. Striped bass eggs and larvae wash down the river in groups, their final location depending upon spawning location and river flow. A lower initial abundance of such groups and a scarcity of dense patches of zooplankton greatly reduces the chance that enough larvae will find sufficient food to survive and maintain the striped bass population.

If our hypothesis is correct, stocking of hatchery fish large enough to avoid the limiting food conditions might be helpful. A hatchery program currently is underway due to pressure on the state legislature from anglers. In 1981, legislation was passed requiring striped bass anglers to purchase a $3.50 striped bass stamp. Sales of this stamp are raising about $2 million per year to be spent on research and management that has potential to enhance the striped bass fishery. Hatchery propagation is also planned to replace fish lost from the estuary by diversions.

All agencies charged with managing the estuarine resources are concerned about the plight of the striped bass and are searching for better answers and practical solutions. Maintenance of adequate outflow is recognized as being essential to protect striped bass. However, the events of recent years and our assessment have led to the conclusion that control of outflow alone is not enough.

We believe that current use of delta channels to convey water for export has contributed to the long-term decline of striped bass. There is good reason to believe that planned increases in export pumping and reduced delta outflows will exacerbate the problems of reduced food production and entrainment unless a properly designed and operated delta water transfer facility is built. An improperly designed project is likely to further reduce numbers of young striped bass, which, in turn, will reduce adult stocks. Further decline in adult stocks will reduce the number of eggs produced and thus, the striped bass population will continue to spiral downward.

Additional prudent action is needed by regulatory agencies to reduce losses to all sources of entrainment, to reduce the deposition of toxic substances, and to maintain adult populations and the needed egg production by experimental stocking. The effect of the additional restrictions that were placed on the fishery in 1982 to reduce fishing mortality should be evaluated as appropriate data become available.

An extensive effort to measure larval striped bass abundance and survival in relation to the zooplankton food supply began in 1984. This study, along with measures of egg production and of the success of the stocking program, may help solve the mystery of California's striped bass decline.

Acknowledgments

We thank the members of the State Water Resources Control Board Striped Bass Working Group for their contributions. We also thank W. Van Winkle, G. Huntsman, and G. Chapman for critiques of the initial analysis by CFG. H. Chadwick, M. Kjelson, K. Lentz, and R. Brown provided useful comments on an early draft of this manuscript. K. Odenweller drew the figures. Funds for this work were provided by Federal Aid in Fish Restoration (Dingell-Johnson) project California F-9-R, "A Study of Sturgeon, Striped Bass, and Resident Fishes"; the California Department of Water Resources; the California State Water Resources Control Board; and the United States Bureau of Reclamation.

References

ARTHUR, J. F., AND M. D. BALL. 1979. Factors influencing the entrapment of suspended material in the San Francisco Bay–Delta Estuary. Pages 143–174 *in* T. J. Conomos, editor. San Francisco Bay: the urbanized estuary. Pacific Division, American Association for the Advancement of Science, San Francisco, California, USA.

BAILEY, N. T. J. 1951. On estimating the size of mobile populations from recapture data. Biometrika 38:293–306.

BAILEY, N. T. J. 1952. Improvements in the interpretation of recapture data. Journal of Animal Ecology 21:120–127.

BROWNIE, C., D. R. ANDERSON, K. P. BURNHAM, AND D. S. ROBSON. 1978. Statistical inference from band recovery data—a handbook. United States Fish and Wildlife Service Resource Publication 131.

CHADWICK, H. K. 1963. An evaluation of five tag types used in a striped bass mortality rate and migration study. California Fish and Game 49: 64–83.

CHADWICK, H. K. 1967. Recent migrations of the Sacramento–San Joaquin River striped bass population. Transactions of the American Fisheries Society 96:327–342.

CHADWICK, H. K. 1968. Mortality rates in the California striped bass population. California Fish and Game 54:228–246.

CHADWICK, H. K. 1977. Effects of water development on striped bass. Pages 123–130 *in* H. Clepper, editor. Marine Recreational Fisheries 2. Sport Fishing Institute, Washington, D.C., USA.

CHADWICK, H. K., D. E. STEVENS, AND L. W. MILLER. 1977. Some factors regulating the striped bass population in the Sacramento–San Joaquin Estuary, California. Pages 18–35 *in* W. Van Winkle, editor. Proceedings of the conference on assessing the effects of power-plant-induced mortality on fish populations. Pergamon Press, New York, New York, USA.

COLLINS, B. W. 1982. Growth of adult striped bass in the Sacramento–San Joaquin Estuary. California Fish and Game 68:146–159.

CONOMOS, T. J., AND D. H. PETERSON. 1974. Biological and chemical aspects of the San Francisco Bay turbidity maximum. Memoires de l'Institut de Geologie du Bassin d'Aquitaine 7:45–52.

DANIEL, D. A. 1976. A laboratory study to define the relationship between survival of young striped bass (*Morone saxatilis*) and their food supply. California Department of Fish and Game, Anadromous Fisheries Branch Administrative Report 76-1, Sacramento, California, USA.

ELDRIDGE, M. B., J. A. WHIPPLE, AND M. J. BOWERS. 1982. Bioenergetics and growth of striped bass, *Morone saxatilis,* embryos and larvae. United States National Marine Fisheries Service Fishery Bulletin 80:461–474.

ELDRIDGE, M. B., J. A. WHIPPLE, D. ENG, M. J. BOWERS, AND B. M. JARVIS. 1981. Effects of food and feeding factors on laboratory-reared striped bass larvae. Transactions of the American Fisheries Society 110:111–120.

FINLAYSON, B., AND T. LEW. 1983. Rice herbicide concentrations in Sacramento River and associated agricultural drains, 1982. California Department of Fish and Game, Environmental Services Branch Administrative Report 83-5, Sacramento California, USA.

FINLAYSON, B., J. NELSON, AND T. LEW. 1982. Colusa Basin Drain and Reclamation Slough monitoring studies, 1980 and 1981. California Department of Fish and Game, Environmental Services Branch Administrative Report 82-3, Sacramento, California, USA.

HALLOCK, R. J., D. H. FRY, JR., AND D. A. LAFAUNCE. 1957. The use of wire fyke traps to estimate runs of adult salmon and steelhead in the Sacramento River. California Fish and Game 43:271–298.

HEUBACH, W. 1969. *Neomysis awatschensis* in the Sacramento–San Joaquin River Estuary. Limnology and Oceanography 14:533–546.

HEUBACH, W., R. J. TOTH, AND A. M. MCCREADY. 1963. Food of young-of-the-year striped bass, *Roccus saxatilis,* in the Sacramento–San Joaquin river system. California Fish and Game 49:224–239.

KOHLENSTEIN, L. C. 1981. On the proportion of the Chesapeake Bay stock of striped bass that migrates into the coastal fishery. Transactions of the American Fisheries Society 110:168–179.

KNUTSON, A. C., JR., AND J. J. ORSI. 1983. Factors regulating abundance and distribution of the shrimp *Neomysis mercedis* in the Sacramento–San Joaquin Estuary. Transactions of the American Fisheries Society 112:476–485.

MASSMANN, W. H. 1963. The "critical zone" in estuaries. Sport Fishing Institute Bulletin 141:1–2.

MASSMANN, W. H. 1971. The significance of an estuary on the biology of aquatic organisms of the middle Atlantic region. Pages 96–109 *in* P. A. Douglas and R. H. Stroud, editors. A symposium on the biological significance of estuaries. Sport Fishing Institute, Washington, D.C., USA.

MILLER, L. W. 1974. Mortality rates for California striped bass (*Morone saxatilis*) from 1965–1971. California Fish and Game 60:157–171.

MILLER, L. W. 1977. An evaluation of sampling nets used for striped bass and *Neomysis* in the Sacramento–San Joaquin Estuary. California Department of Fish and Game, Anadromous Fisheries Branch Administrative Report 77-3, Sacramento, California, USA.

MILLER, P. E. 1978. Food habit study of striped bass post yolk-sac larvae. Johns Hopkins University, Chesapeake Bay Institute Special Report 68, Baltimore, Maryland, USA.

ORSI, J. J., AND A. C. KNUTSON, JR. 1979. The role of mysid shrimp in the Sacramento–San Joaquin Estuary and factors affecting their abundance and distribution. Pages 401–408 *in* T. J. Conomos, editor. San Francisco Bay: the urbanized estuary. Pacific Division, American Association for the Advancement of Science, San Francisco, California, USA.

PGE (PACIFIC GAS AND ELECTRIC COMPANY). 1981a. Contra Costa Power Plant cooling water intake structures 316(b) demonstration. PGE, San Francisco, California, USA.

PGE (PACIFIC GAS AND ELECTRIC COMPANY). 1981b. Pittsburg Power Plant cooling water intake structures 316(b) demonstration. PGE, San Francisco, California, USA.

RICKER, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada Bulletin 191.

RILEY, G. A. 1947. A theoretical analysis of the zooplankton population of Georges Bank. Journal of Marine Research 6:104–113.

SCOFIELD, E. C. 1931. The striped bass of California (*Roccus lineatus*). California Division of Fish and Game, Fish Bulletin 29.

STEVENS, D. E. 1977a. Striped bass (*Morone saxatilis*) year class strength in relation to river flow in the Sacramento–San Joaquin Estuary, California. Transactions of the American Fisheries Society 106:34–42.

STEVENS, D. E. 1977b. Striped bass (*Morone saxatilis*) monitoring techniques in the Sacramento–San Joaquin Estuary. Pages 91–109 *in* W. Van Winkle, editor. Proceedings of the conference on assessing the effects of power-plant-induced mortality on fish populations. Pergamon Press, New York, New York, USA.

STEVENS, D. E. 1980. Factors affecting the striped bass fisheries of the West Coast. Pages 15–28 *in* H. Clepper, editor. Marine Recreational Fisheries 5. Sport Fishing Institute, Washington, D.C., USA.

TURNER, J. L. 1966. Seasonal distribution of crustacean plankters in the Sacramento–San Joaquin Delta. California Department of Fish and Game, Fish Bulletin 133:95–104.

TURNER, J. L., AND H. K. CHADWICK. 1972. Distribution and abundance of young-of-the-year striped bass, *Morone saxatilis*, in relation to river flow in the Sacramento–San Joaquin Estuary. Transactions of the American Fisheries Society 101:442–452.

TURNER, J. L., AND W. HEUBACH. 1966. Distribution and concentration of *Neomysis awatschensis* in the Sacramento–San Joaquin Delta. California Department of Fish and Game, Fish Bulletin 133: 105–112.

WHIPPLE, J. A., M. B. ELDRIDGE, AND P. BENVILLE, JR. 1981. An ecological perspective of the effects of monocyclic aromatic hydrocarbons on fishes. Pages 483–551 *in* S. J. Vernberg, A. Calabrese, F. P. Thurberg, and W. B. Vernberg, editors. Biological monitoring of marine pollutants. Academic Press, New York, New York, USA.

An intense commercial sturgeon fishery existed in the 1800s, but was closed in 1901 after the catch plummeted. The fishery reopened in 1910, was closed in 1917, and in 1954 reopened for recreational purposes only (SWRCB,430,453). Angling is popular in the Sacramento River up to Colusa, in the Delta (SWRCB,405,35-36), and in the bays. Sturgeon are taken in San Francisco Bay where they congregate to feed during the herring runs (SWRCB,430,454). Party boats reportedly harvested 2,400 sturgeon in 1967. There is no information on the recent magnitude of the fishery.

Adult steelhead migrate upstream from the ocean during the spring through fall. Spawning occurs from December through April in tributaries above the Delta. Like salmon, steelhead return home to their natal stream; unlike salmon, not all adults die after spawning. Steelhead are known to have spawned up to four or more times (SWRCB,405,60; SWRCB,450,5-7). There are several seasonal runs of steelhead migrating through the Delta (SWRCB,405,59-60; SWRCB,450,5-6). The size of the recreational fishery for steelhead adults and juveniles is unknown.

- Species of Concern

The Sacramento splittail, Pogonichthys macrolepidotus, is one of two species of special concern because its distribution is restricted to the Bay-Delta Estuary and it has recently declined in abundance (USFWS,35,1). The other, the Delta smelt, Hypomesus transpacificus, once abundant in Suisun Marsh and the Delta, has undergone a precipitous decline since the early 1970s (USFWS,35,20). Both fish have been recommended as candidate species by the USFWS to be studied to determine whether they should be added to the federal Endangered and Threatened list (USFWS,35,11)[1].

The splittail is a category 2 candidate and the Delta smelt is a category 1 candidate. (A category 1 species is one for which the USFWS has substantial information to support a proposal for listing as endangered or threatened. A category 2 species is one for which information available indicates that a proposal for listing is possibly appropriate but that the data available are not conclusive.)

A petition was submitted June 9, 1989 to the Fish and Game Commission to list the Delta smelt as an endangered species under the California Endangered Species Act. On August 29, 1989, the Commission accepted the petition and for one year the Delta smelt was a candidate species. During this time DFG staff reviewed the pertinent data and recommended that the species be listed as threatened. The Fish and Game Commission on August 31, 1990 decided that there was insufficient evidence to list the species at all and that further studies on the species should be conducted. The Delta smelt remains a species of Special Concern.

1/ *Listing refers to a process established under state and federal Endangered Species Act by which Native spec[ies] are identified. Those listed are determined to be in immediate jeopardy of extinction ("endangered") or [to be] present in such small numbers throughout their range that they may become endangered if their present environment worsens (rare plant or threatened species) (California Fish and Game Code Sections, 7, and 2068; 16 USC Section 1531 et seq.)*

2/ *Section 670.1, Title 14, CCR and Sections 2072 and 2072 and 2072.3 of the Fish and Game Code.*

FROM: Water Quality Control Plan for Salinity. S.F. Bay/ Sacramento-San Joaquin Delta Estuary. 91-15WR May 1991 SWRCB

The USFWS was petitioned by the California-Nevada Chapter of the American Fisheries Society on June 26, 1990 to list the Delta smelt as an endangered species under the federal Endangered Species Act. A USFWS administrative finding on the petition request stated that substantial information was presented such that listing may be warranted. This initiates a one year review period, from the date of receipt of the petition (6/29/90), in which the USFWS will gather information on which to make a determination on whether to list the Delta smelt. Until this determination is made, its status remains a category 1 candidate species.

The information on resident freshwater species and other anadromous fish presented in the Phase I hearing was mostly descriptive. No quantitative data were presented on the relationship between population abundance, distribution and salinity regimes.

Subsequent investigations have revealed that the Delta smelt inhabit the open surface water of the Delta and Suisun Bay and live about one year. The adult Delta smelt spawn in freshwater between the months of December and April (Moyle, 1976) and most apparently die after spawning. The buoyant larvae are washed downstream until they reach the entrapment zone, where the currents keep them suspended and circulating with the zooplankton, which is their food. During the larval stage, from approximately April through June, the smelt are not yet of sufficient size to be efficient swimmers and effectively pursue their prey. Therefore, a high density of prey items in suitable habitat offers an advantageous environment for rearing (Moyle, pers. comm., 10/89). The smelt grow rapidly and within six to nine months reach adult length. In the next three months the smelt become sexually mature and move up into the freshwater to spawn. All sizes are found primarily in the main channels of the Delta and Suisun Marsh, and the open water of Suisun Bay (Moyle, 1989). Delta smelt, most of the year, are found in water of less than 2 ppt TDS (2.9 mmhos/cm EC) and occasionally are found in water up to 10 to 12 ppt TDS (14.6 to 17.5 mmhos/cm EC) (Moyle, 1989). Spawning occurs in freshwater when the water temperatures are between 7 and 15°C (44.6 to 59°F) (Wang, 1986).

4.0.5.2 Bay Habitat

Suisun, San Pablo, San Francisco and south San Francisco (South) bays are considered here. Since, for this Plan, Suisun Bay is considered to be part of the Bay, it is included here for purposes of discussion.

Fishery Habitat Protection (Entrapment Zone)

As in the freshwater portions of the Estuary, phytoplankton and zooplankton form important parts of the food chain in the more saline portions of the Estuary. Many fish rely upon the presence of copepods and cladocerans, e.g., _Neomysis_, _Corophium_, and _Lagunogammarus_. These zooplankton in turn feed upon detritus and upon phytoplankton, the primary producers. Maximum phytoplankton production for this Estuary appears to occur when outgoing freshwater and incoming ocean water mix at approximately the upstream end of Suisun Bay (USBR,111,28; USBR,112,53-70). The area just downstream of this location, known as the entrapment zone, is a concentration site for certain diatoms, detritus, _Neomysis_ and other zooplankton (USBR,111,27).

FROM: WATER QUALITY CONTROL PLAN FOR SALINITY S.F Bay/Sacramento-San Joaquin Delta Estuary 91-15WR May 1991 SWRCB

5.6.1 Present Conditions

5.6.1.1 Background: D-1485 Objectives

Striped bass are specifically protected in D-1485 (Table II,38,39,40). These requirements evolved out of negotiations conducted among DFG, DWR, USFWS, and USBR prior to the 1978 hearing as part of a draft Four-Agency agreement; this agreement was never signed (DFG,25,133). Salinity (EC) objectives at Antioch and at Prisoners Point on the San Joaquin River establish a striped bass spawning area estimated to be about 17 miles in length from April 1 to May 5 in all water years. These objectives were first established (in an earlier form) by Water Right Decision 1379, adopted in July 1971. They were established after a review of an earlier State Board Resolution (68-17; Supplemental Water Quality Control Policy) indicated that striped bass spawning was not being protected. The recommended protection measures were similar to those proposed by a Department of Interior task force on Delta salinity objectives (Decision 1379, 32).

The objective at Antioch is 1.5 mmhos/cm EC (the first two weeks of protection are provided by a Delta Outflow Index requirement of 6,700 cfs rather than an EC objective to provide some ramping capability for the CVP and SWP water projects). This objective also includes a relaxation provision when the SWP or CVP declares deficiencies in delivery of firm project supplies. Upstream, the objectives provide for a maximum of 0.55 mmhos/cm EC at Prisoners Point; no relaxation provision is included.

In May, June and July, minimum Delta Outflow Index flows and limitations on export levels come into effect for protection of young bass. These requirements were designed to help move eggs and young into suitable nursery areas and to reduce entrainment into the SWP and CVP export systems. The Delta outflows were also expected to provide equivalent protection for later spawning in the San Joaquin River, at least in wet, above normal, and below normal water years; outflows during these periods were expected to be higher than the 6,700 cfs estimated to be required to maintain the 1.5 mmhos/cm EC at Antioch under steady-state conditions (1978 Delta Plan, VI-4). Provisions for periodic closure of the Delta Cross Channel gates (to reduce translocation of Sacramento River striped bass eggs and young into the central Delta) and recommendations (not mandatory requirements) for the operation of the projects' fish recovery facilities are included in D-1485. Other than the Delta Cross Channel gate closure, there are no specific objectives for protection of spawning or young bass in the Sacramento River.

5.6.1.2 Current Status

The adult population of striped bass in the Estuary has declined in recent years to about one-third or one-fourth of the population levels seen in the 1960s. A variety of sampling programs are employed to monitor various components of the striped bass population (see Appendix 5.4.1). While the decline rates and patterns may vary somewhat, all programs measuring striped bass abundance show large declines (DFG,25,6,9). The primary means of evaluating the overall condition of striped bass between years has been the Striped Bass Index (SBI). The objectives in D-1485 were designed to maintain the SBI at a long-term average of 79 (the so-called "without project" conditions). This goal has not been achieved; in 1990, the actual SBI reached an all-time low of 4.3; 1988 was the second-lowest on record with 4.6, and in 1989 the SBI was 5.1. The average SBI for the period 1979-1990 is 19.1 (see Appendix 5.4.2).

In the late 1970s declining striped bass populations indicated that the requirements in D-1485 for protection of striped bass were not achieving their intended and expected results. In response, the State Board organized a Striped Bass Work Group composed of staff from several state and federal agencies and outside consultants to investigate the cause(s) of this decline and to make recommendations on actions to correct it. Subsequent discussion and data analysis have resulted in an expanded and refined list of possible causative factors. These are discussed in Appendix 5.4.3. The relationship of the export area striped bass fishery to the Estuary fishery is discussed in Appendix 5.4.4. In large part, while the reasons for the striped bass decline are known, the relative importance of each factor is not completely understood (WQCP-DFG-3).

5.6.2 State Board Considerations

General: Salinity Objectives

Salinity objectives for striped bass apply to the spawning conditions and limitations for adult striped bass in the San Joaquin River. Striped bass in the Sacramento River spawn well above the influence of ocean-derived salinity, and, unlike the San Joaquin River, water quality and river flow are sufficient to prevent the formation of upstream salinity barriers to fish passage due to land-derived salts. No D-1485 objectives or advocated positions consider this area, and no alternatives are offered for consideration.

The D-1485 salinity objectives were expected to provide minimal, yet adequate, spawning habitat from approximately Antioch to Prisoners Point to sustain a healthy striped bass population. However, the continuing decline indicates that some new actions must be considered. Therefore, as one part of an overall program to increase protection for estuarine habitat, it is appropriate to consider modifying the three D-1485 San Joaquin River spawning objectives.

This section considers temperature in addition to salinity objectives at Antioch and Prisoners Point:

5.6.2.1 Antioch: Period of Protection for Spawning
5.6.2.2 Antioch: Relaxation Provision
5.6.2.3 Prisoners Point: EC Modification
5.6.2.4 Prisoners Point: Relaxation Provision
5.6.2.5 Temperature Objectives

Because no information on salinity requirements for shad was presented or obtained from other sources, no salinity objective is offered. However, shad feed on Neomysis and other zooplankton during their spawning migration through the Delta (see Table A4-8), which suggests that the entrapment zone may serve an important function for adults as well as young of the year of this species. The nature of this function warrants study.

The Delta and its tributary streams, especially in the Sacramento Valley, are major spawning and nursery areas for American shad. If young shad react to high temperatures as many other fish species do, they are most sensitive during their first few days to weeks of growth. Young are found in the Delta and at the SWP facilities in midsummer, indicating substantial summer spawning activity within or near to the Delta (DFG,23,8-10). DFG observations indicate that these eggs and young are susceptible to considerable risk from elevated water temperatures: eggs appeared deformed and failed to develop normally when water temperatures were 70°F and above (Michael Meinz, SWRCB, pers. comm., October 1989). As indicated in Table A4-8, the optimum spawning temperature for American shad is between 60° and 70°F. The temperature objective for salmon may serve to protect American shad to some degree. The actual status and population trend of American shad remains unclear. Substantial additional work is recommended in the areas of population, reproduction and ecological requirements for this species, to provide a firm basis for possible future actions.

5.7.3 Potential Objectives

On the basis of the foregoing discussion, no objectives for protection of American shad are proposed at this time.

5.8 Delta Smelt

5.8.1 Present Conditions

Currently there is no D-1485 objective specifically for the protection of the Delta smelt, *Hypomesus transpacificus*, in the Delta. The Delta smelt is endemic to the Sacramento-San Joaquin Delta-Estuary (Moyle, 1989) and, at present, is not known to exist anywhere else in the world (Federal Register, Volume 154, No. 4). Their range extends from below Mossdale on the San Joaquin River and Isleton on the Sacramento River to Suisun Bay, Carquinez Strait and San Pablo Bay during portions of the year (Moyle, 1976).

The population of Delta smelt, once very common in the upper Estuary, has been declining over time and appears to be critically low. Several sources of information regarding long-term trends in Delta smelt numbers are available, the primary ones being: (1) DFG, mid-water trawl surveys (Stevens et al., 1990); (2) research and monitoring data from the University of California at Davis (UC Davis) (Moyle and Herbold, 1989; Moyle and Herbold, 1990); and (3) and screen salvage data from the Byron and Tracy Pumping Plants (SWC,1990;DFG,17,1-20). The data from the

FROM: Water Quality Control Plan for Salinity. S.F. Bay/ Sacramento - San Joaquin Delta Estuary. 91-15WR May 1991 SWRCB pumping plants are not very reliable due to the lack of an effective quality control program which may have resulted in misidentification (e.g., other species of smelt or other fish altogether) and other recording errors (SWC, 1990). Each data set however indicates a decline in the numbers of Delta smelt.

DFG (Stevens et al., 1990) stated that like the summer townet survey, the fall midwater trawl survey indicates that abundance of Delta smelt has been highly variable and has suffered a major decline. Bay survey catches show a striking decline in Delta smelt abundance after 1981, and since 1981 there has been an irregular but persistent decline. Part of this is due to the fact that the four of the last five years were low flow years and the population has been concentrated in the Delta. In the seine survey, the lowest average catches of adult Delta smelt occurred in 1980 and 1984-1989. The persistent low catches from 1984-1989 are consistent with the population decline exhibited by the midwater trawl and summer townet surveys. The DFG concluded that "the relatively stable, albeit low, population is not in imminent danger of extinction," however the Delta smelt may well "become an endangered species in the foreseeable future."

The Delta Smelt Index (Stevens and Miller, 1983) has been calculated annually from 1967-1990, except for 1974 and 1979 when no surveys were conducted; it shows an overall decrease in population size, especially from 1980-1988 (see Table 5-3; Figure 5-4). The population has fluctuated a great deal over the years; however, since 1983, the population has been consistently low. The UC Davis data show a similar trend. Several factors have possibly contributed to the decline, including invasions of exotic phytoplankton and invertebrates, entrainment into diversions and modification of the Delta smelt habitat.

5.8.2 State Board Considerations

Delta smelt are affected by the location of the entrapment zone, which appears to be important to their survival. When the entrapment zone is located in the deep, narrow channels of the Delta and Sacramento River, or in Carquinez Strait and the deeper parts of San Pablo Bay, primary productivity is lower (Moyle and Herbold, 1989). When the entrapment zone is located in Suisun Bay, the nutrients and algae can circulate in sunlit water, allowing algae to grow and reproduce rapidly, in turn, providing an abundance of food for plankton-feeding fish, such as the Delta smelt (Moyle, 1989). Years of major decline in the Delta Smelt Index occurred not only in dry years (1987,1988) but also wet years (1982,1986); in both cases, the entrapment zone moved out of Suisun Bay. Thus, Stevens and Miller (1983) did not develop a regression model for Delta smelt because all of the correlations between their abundance and flow measurements were not statistically significant. One of the strongest determinants of Delta smelt abundance is high primary productivity (as reflected by phytoplankton abundance) in late spring, April to June (Moyle and Herbold, 1989).

Table 5-3

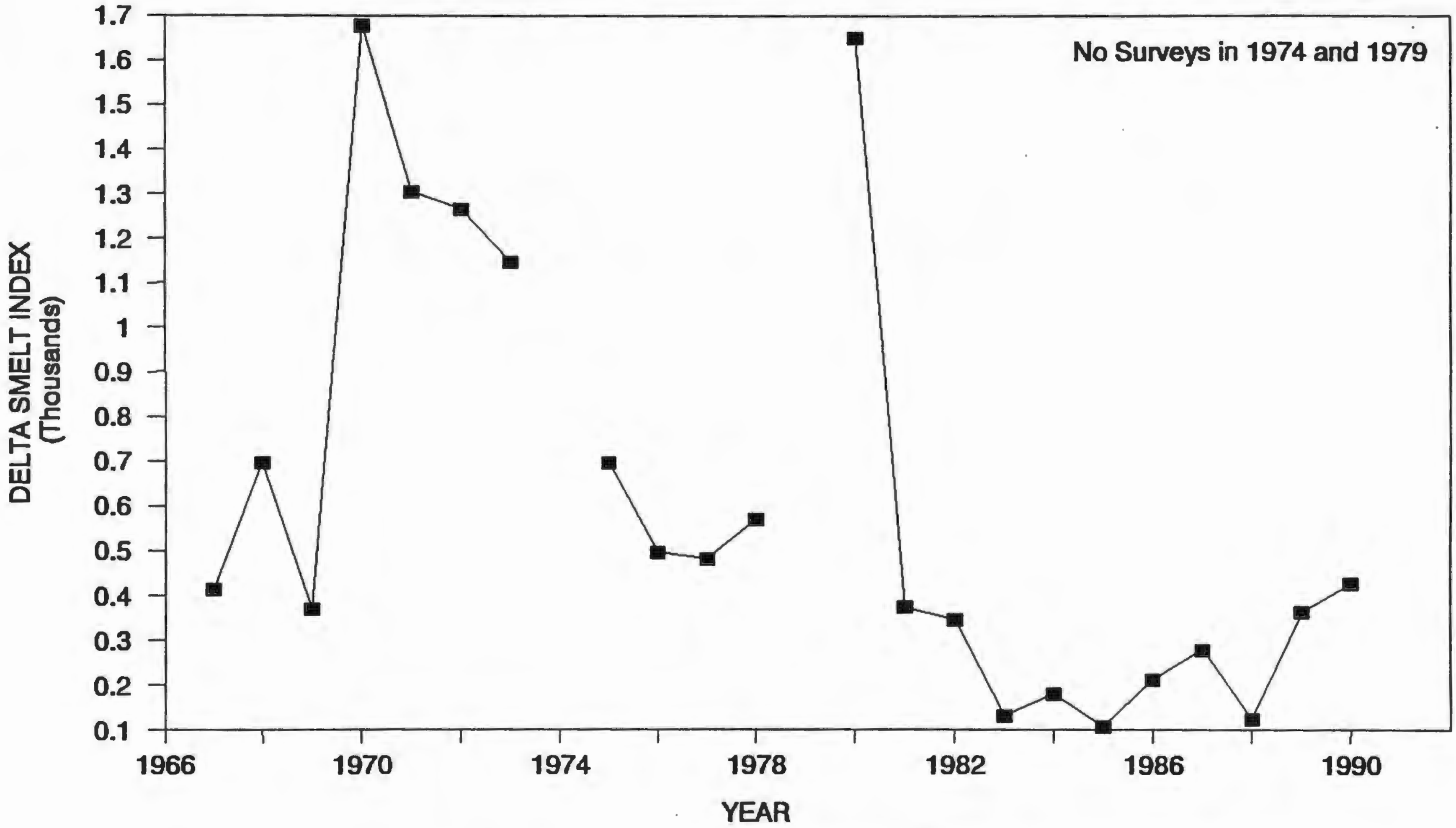
DELTA SMELT ABUNDANCE INDEX
MIDWATER TRAWL SURVEY
1967-1990

YEAR	INDEX
1967	415
1968	697
1969	371
1970	1678
1971	1305
1972	1267
1973	1146
1974	
1975	698
1976	497
1977	483
1978	570
1979	
1980	1651
1981	375
1982	346
1983	132
1984	181
1985	109
1986	212
1987	280
1988	126
1989	364
1990	427

Note: Trawl surveys were not conducted in 1974 & 1979.

From Stevens, D.E., L.W. Miller and B.C. Bolster. 1990. Report to the Fish and Game Commission: A status review of the Delta smelt (Hypomesus transpacificus) in California.

Figure 5-4 Delta Smelt Index Values



Stevens, D.E., L.W. Miller and B.C. Bolster. 1990. Report to the Fish and Game Commission: A status review of the Delta smelt (Hypomesus transpacificus) in California. Department of Fish and Game.

Further study will be required to define more specifically the habitat requirements of the Delta smelt and identify the variables contributing to their decline. The Fish and Game Commission has made a decision not to place the Delta smelt on the endangered species list; however, further analyses are being conducted in part for the requirements of the state and federal Endangered Species Acts.

Delta smelt habitat indicates a salinity preference of less than 2 ppt and seldom greater than 10 ppt (Ganssle, 1966 in SWC 1990) (less than 15 mmhos/cm EC). Another critical life history characteristic is that they spawn in sloughs and channels in the upper Delta, although spawning has also been recorded in Montezuma Slough in Suisun Bay (Moyle, 1989; SWC, 1990). They spawn from January through May and where they spawn may be influenced by the location of the fresh-saltwater interface during this time period (Moyle and Herbold, 1990). Peak numbers of smelt are salvaged at the SWP and CVP pumping plants each year during April and May (SWC, 1990, Figure 7). These smelt are either the spawning adults or the larval smelt (the information presented does not indicate which stage of development). One effective means of reducing impacts to the Delta smelt would be to reduce entrainment into the SWP and CVP pumping plants.

The location of the entrapment zone appears to be important to the survival of the Delta smelt. Although the precise level of salinity that separates acceptable and unacceptable spawning conditions is not known, existing knowledge suggests that salinities of 2 ppt or less are desired in Suisun Bay from March through June. The same needs exist for protection of the Delta smelt nursery area in Montezuma Slough (WQCP-USFWS-5). As the entrapment zone is a flow issue, this will be discussed in the Scoping and Water Right Phases of the proceedings.

There is insufficient information to set an EC or salinity objective for spawning for Delta smelt at present. Further study may provide an objective to help reverse their decline. Further studies are proposed for determining, with greater accuracy, the abundance and the factors affecting Delta smelt abundance in the Delta. The details of these studies will be discussed in the Program of Implementation, Chapter 7. Subsequent review of data may lead to appropriate water quality objectives.

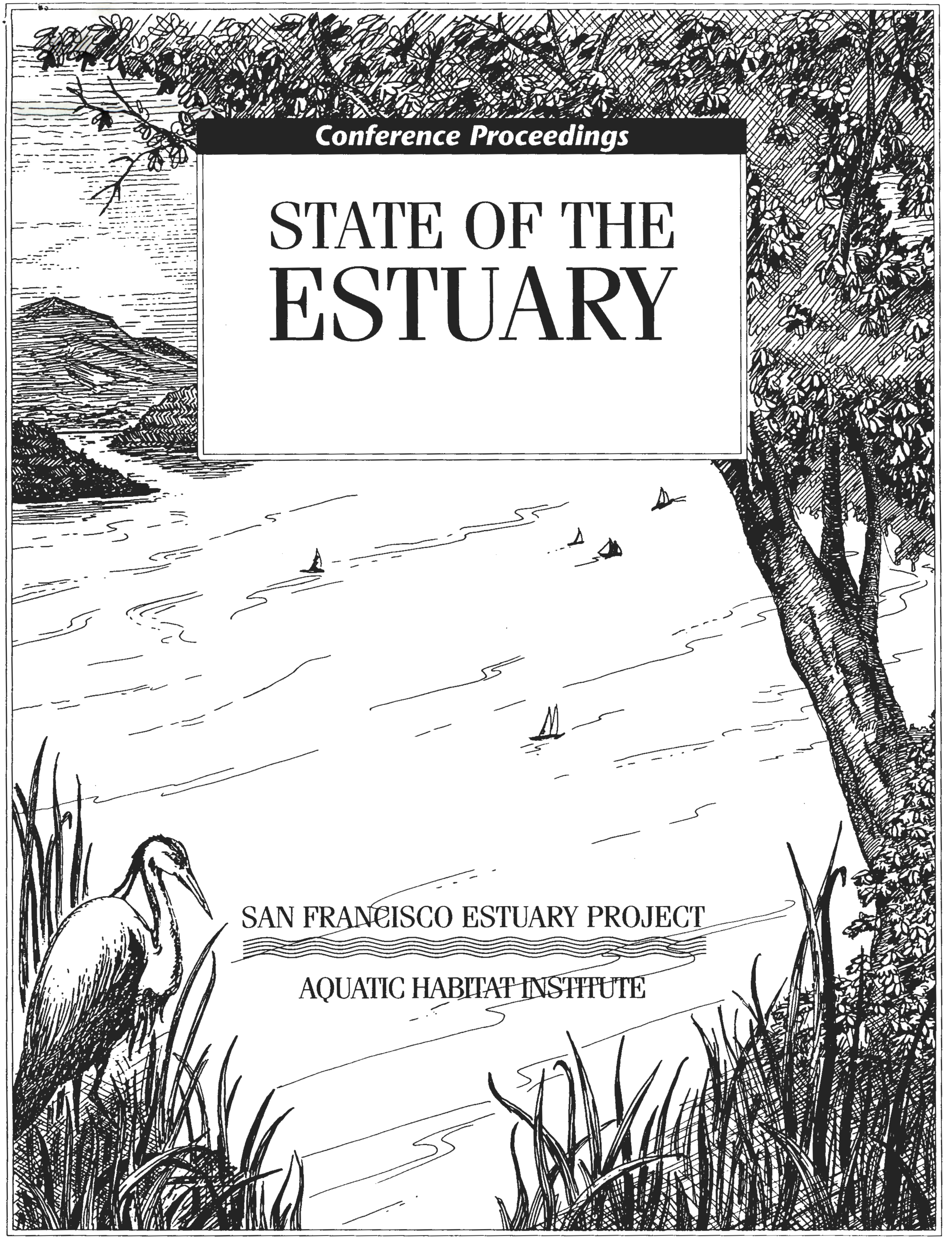
5.8.3 Potential Objectives

No potential salinity or temperature objectives can be specified at this time.

5.9 Other Resident Fish in the Bay-Delta Estuary

5.9.1 Present Conditions

The Department of Fish and Game presented information on several species of resident fish found in the Bay-Delta Estuary (Appendix 4). The information on water quality habitat criteria was of a very general nature. Some species, for example, were said to have a relatively greater preference, or tolerance, for higher levels of dissolved solids or turbidity than other species. DFG recently submitted a report on white sturgeon that states the fish move up or downstream in response to salinity changes and that management of the volume of freshwater flow may be important in maintaining the sturgeon population (WQCP-DFG-1).



Conference Proceedings

STATE OF THE ESTUARY

SAN FRANCISCO ESTUARY PROJECT

AQUATIC HABITAT INSTITUTE

BIOLOGICAL RESOURCES PANEL DISCUSSION

Brian Hackney, Moderator
KGO TV-7

Hi everybody, and thanks for coming. This is the last session of the afternoon for the State of the Estuary Conference. I'm Brian Hackney from KGO. Joel Bartlett was supposed to be here, but he came up with another engagement he had to make. So, we're going to be talking about the Biological Resources of the Estuary, and to begin with, we have five panelists. I will introduce them as we hit each one of them in sequence. The first is Perry Herrgesell, who is a Fish and Wildlife Manager for the California Department of Fish and Game of the Bay-Delta Project in Stockton, and he will be discussing some of the results of a study that he's done on the state of the Estuary as regards to biological resources — where we stand, the poor shape it's in and also what we can do about it. So, Perry, if you'd like, you can come up and make your presentation.

Comments by Perry Herrgesell
California Dept. of Fish and Game

Good afternoon — to those of you that are left anyway. What is happening with the fish and wildlife resources in the Sacramento, San Joaquin, Delta and San Francisco Bay? That question is often asked, and I think the answer really depends on who you listen to. Mike has given a very good presentation here today. In fact, almost everything I will say, you've heard already in Mike's presentation earlier on. But we'll go through it anyway, maybe some people can pick it up if you hear it the second time. But I think again the answer depends on who you listen to.

For example, a report by the Bay Area Dischargers Association in 1986, said this:

> "On the one hand there is evidence that conditions are good. Some of their evidence is anecdotal, newspaper reports of fishing success, for example. Some is scientific, such as measures of water quality showing that Bay waters meet standards. There is also a lack of evidence of bad conditions. People swim in the Bay; they fish in it. It does not smell as bad as it did years ago. One might ask what's the problem?"

Well, a report by the State Water Contractors, who are the users of the water, said this in 1987:

> "San Francisco Bay is not in or approaching a state of crisis. The Bay is not in danger of ecological collapse; it does not exhibit characteristics of a system on the verge of collapse. Bay fisheries and the supporting ecosystem as a whole are in good condition. Fishery problems involving striped bass and Dungeness crabs are largely caused by conditions outside the Bay. Water quality in the Bay is generally good and has improved in recent years."

And then, in 1991, in the report by the Citizens Alliance to Restore the Estuary, (Barry Nelson was here just awhile ago and he flashed this report in front of you), we read this:

> "Although the Bay indeed looks cleaner than it did 10 or 20 years ago, the problems outlined above, if left unchecked, will transform the Bay into a monument to shortsightedness. In thirty years' time, the Bay could be ringed by a mosaic of congested freeways and industrial parks, many of them vacant, built on the Bay's last remaining seasonal wetlands. With the loss of the wetlands, many of the Bay's already tenuous wildlife populations would disappear altogether, and West Coast migratory ducks and shorebirds would be deprived of one of their last refuges as they make their yearly 10,000-mile journeys. Without appropriate source control measures, increased industrial and municipal pollution, coupled with increased water diversions could leave the Bay little better than a huge toxic dump. Striped bass and salmon populations already severely depleted would be eliminated. The remaining fish and shellfish would be too contaminated to eat. Fisherman's Wharf shops and restaurants would be perched on the edge of a lifeless body of water, bereft of the fishing boats, pelicans and sea lions that delight millions annually."

Well, what's the truth, and what can be done about it? That's the topic of today's session. Jim McKevitt, on the panel over here with the Fish and Wildlife Service and I have kind of decided to split the pie today. I'll address fishery resources, and he'll address wildlife resources associated with the Bay; and in that process my approach will be to first of all discuss the trends and some selective fishery resources, then spend a little time talking about the causes of those trends, and, finally, what potential actions could be implemented to restore the Estuary and protect the Estuary at the same time.

Alright, what's happening to the fishery resources in the Estuary? When I'm asked this question, generally by news media and reporters, I have a standard answer that is fairly accurate. That answer is that most species that we have monitored for some time appear to be in a downward trend, and I'll spend a few minutes discussing some of the specifics on which I have based this generalization. We've been monitoring striped bass abundance in the Estuary since about 1959, and what we've found can be seen in this figure. There has been an irregular but steady decline in production of young striped bass during this time period.

In the first summer of life, year classes that have added to the populations during the past seven years were only about 1/3 as abundant as those produced during the previous 17 years of study. In fact, the 1990 striped bass index, which is based on young, and also on some of the adult fish, was the lowest during the period of record. The number of legal size adults fell to a record low of about 500,000 fish. Now, that represents a decline from about 1.6 to 1.9 million fish that were present in the early 1970s.

We have another fairly long database and dataset for another important fish in the system, and that species is the Delta smelt. These fish are confined to the upper Sacramento-San Joaquin Estuary, and historically, the upstream limits have been around Sacramento in the Sacramento River, and about Mossdale in the San Joaquin with the lower limits being in Suisun Bay. These graphs that are on the screen now show that the trend is very obvious. Since the early 1980s, the abundance of Delta smelt has been sharply down. I won't get into the details on this panel, but you can see there are 4, 5, or 6 different indices that were used to measure that. These declines have been so distinct and alarming that this species was recently proposed as a candidate for endangered species classification in California. But it was not listed by the Fish and Game Commission, and since that time, the federal agencies have petitioned federally to have it listed there. The resolution of that petition really remains to be seen but the population trend, I think, is obvious.

We also have some information about organisms that form the base of the food chain. If one looks at the abundance of the four species of copepods, which are the small food organisms, small crustations in the system that feed larval fish, one can easily see that *Acartia* is the only species of copepods that has not undergone a severe long-term decline. That's probably because it is a salt-tolerant species. The peaks that you see on the *Acartia* graph, were during low flow years when it seemed to do better under the high salinity conditions.

Generally, during the last ten years, you can seen the means of the other species have dropped below half of what they were in the previously ten years of our study.

The starry flounder is an important recreational fish that has been studied for a shorter period of time, about ten years. Yet the apparent trend is similar to other species that we've talked about. This figure shows information and data from the Interagency Ecological Delta Outflow Study Program, and it shows a very sharp decline in starry flounder catch since 1983. The last four years on the graph here are the lowest in terms of flounder abundance that we've seen. And note that the decline has been the sharpest in San Pablo Bay which from 1985 to 1988 yielded less than 10% of the starry flounder captures at the same stations during the period 1980 through 1984.

Chinook salmon is another important species in the system. The species grows to about 1-1/2 meters, and that's larger than any of the other species of salmon. They probably provide the largest commercial fishery near the San Francisco Bay and also support a very large sport fishery in the ocean and a modest fishery in the Bay. As a general rule, the abundance of native runs of Chinook Salmon have declined over the recent years as well. The most reduced run however, is the winter-run, which was listed as endangered by the State Fish and Game Commission after its population was estimated to be less than 500 fish.

Well, I don't want to go on too much longer with information on trends, but I do want to summarize this part of the presentation with a graph that shows the catch of the six most abundant species that we have collected during the September mid-water trawl, a survey which was carried out by the Department of Fish and Game under the Interagency Ecological Study Program during the period 1967 to 1988. The figure presents information for striped bass, threadfin shad, white catfish, Delta smelt, American shad, and longfin smelt. And, once again, you can see that the catches for these species, combined, in thc last ten years have been 8 to 10 times lower than those in the late '60s, and about 3 to 4 times lower than catches in the early and mid 1970s. Again, the predominant trend for these six species has been down.

That provides some substantiation for my standard answer that I usually give to people that most of the species that we have monitored for some time appear to be on a downward trend. And now I'd like to turn to a very brief discussion about generic causes for these trends, and a lot of this information you've heard in the last two days also. I won't really spend a lot of time on justification that these are the only causes for these trends, because they well indeed may not be the only causes.

First of all, one of the main impacts has been outflow reductions and altered flow regimes. You've just heard a session dealing with this problem here a few minutes ago. Several long-term studies that have been carried out by the Interagency Ecological Study Program have shown the importance of the amount and of the timing of freshwater outflow from the Delta to estuarine species including striped bass, bay shrimp, starry flounder, longfin smelt and several others.

These flows are important because they provide reduced salinities in the system and therefore allow a greater estuarine habitat availability which results in lowered competition within the species. These flows are important because they provide transport of larvae to the productive entrapment zone. There has been a lot of talk about that. They're important because they allow increased nutrient input into the system and possible increases in food production. Flows are important to the system because they provide improved circulation patterns in the Estuary, and they're important because they are able to transport larval fish away from water diversions that are centered in the Central Delta.

What has happened is that water development projects have reduced the total annual volume of water to the Estuary by as much as 58% in recent years, at least during 1986 through 1989. Water projects have altered the timing of the flows as well. To give you some feel for the potential impact of that, you should realize that the reservoirs in the estuarine watershed are capable of storing 27 maf of water, which is more than reaches the Estuary in the average year. There are also more than 7,000 diversions within the Estuary, and diversions upstream of the Delta remove about 9,000,000 acre feet of water. Beyond that, in the upper watershed, about 7,000,000 acre feet of water are diverted from the Delta.

That leads to a consideration of the second cause for the decline, and that is the direct effect of diversions. These two causes, flow reductions, which I first mentioned and then diversions, of course, are interrelated. The more diversions you have from the system, the lower the outflows are. The direct effect of diversions has had a very significant impact on the striped bass population. That conclusion is based upon at least three facts the Department of Fish and Game has developed over the years:

1) It's based on the fact that the initial stages of the decline for striped bass and young bass abundance during the period 1971 through 1976, apparently occurred in response to increased State Water Project and CVP exports.

2) It's based on the fact that the initial and most striking decline was primarily in the Delta, a portion of the nursery where major diversions are located.

3) It's based on the fact that the Dept. of Fish and Game's loss estimates of bass smaller than 20 mm at the State Water Project and the CVP are very substantial. For example, in 1985, 73% of the 20mm stage bass were reduced or taken out by the Water Project's pumps.

So the population, at least of the young ones at the 20mm stage were reduced by 73%, and that was in a dry year — 1985. In a wet year, 1986, there were still 31% of the small bass that were affected by the pumping operations. Another dry year, 1988, had an 84% reduction. Some of these kinds of reductions will obviously affect year class strength, and that results in reduced adult stocks and therefore lower egg production and a decline in the bass population as a whole.

A third cause for population declines in the Estuary is related to the proliferation of introduced or exotic species into the system. According to the State of the Estuary Report which Mike talked about earlier, there are more than 35 species of the Pacific Rim origin — invertebrates, fish and algae that occur in the Bay. Fifteen of those have been discovered since 1973. So you can see, there's been quite an influx of introduced or exotic species into the Bay. At the current rate, we're adding at least one exotic species into the Estuary each year, and that is an impressive change in an ecological system.

One of the most recent introductions is the Asian clam (*Potamocorbula*) and you've heard some talk about that as well. The larvae of this organism apparently entered the system in the ballast water of a cargo ship, and its impact in the system is associated with its high reproduction rates and an ability to filter massive amounts of water. U.S.G.S. scientists believe that filtration by this clam is probably the cause of the extremely low values of chlorophyll in the Bay during 1988. And Fred Nichols, who all of you know, has noted that *Potamocorbula* could really have a very profound effect on the make-up of the benthic community and entire food web.

Pollutants, particularly toxic pollutants like mercury, selenium, tributyl-tin, chromium, pesticides and various other hydrocarbon by-products most certainly pose a threat to aquatic resources in the Estuary, although regulators have made great strides through the NPDES system at cleaning up the discharges. Still, there's a long way to go with respect to solving problems associated with sub-lethal and chronic effects of both industrial discharges and urban runoff. We believe that toxicity from waste discharges contributes to a deterioration in habitat quality for striped bass, and other fishes, while other folks — and one of the sources quoted was Davis, (1991) — report that concentrations of toxic PCBs in adult starry flounders have been shown to be sufficient to reduce reproduction success. Other examples exist as well as these. They include selenium concentrations in ducks, mercury in bass, and so on. Much remains to be done in the area of toxic effects in the system.

Dredging is another factor that affects biological resources in the Estuary. The main impact associated with this activity appears to be resuspension and release of sediments and pollutants into the water column. One of the most recent and controversial effects of dredging has been dredge spoil disposal near Alcatraz, which has allegedly resulted in lower catch per-effort statistics in recent years for party boat fishermen in that area.

Poaching is another factor that might be contributing to the decline of striped bass. It can be defined as any form of illegal fishing like netting, overlimits, retention of under-sized fish, and the illegal sale of fish no matter how they're taken.

Striped bass poaching has been a very persistent problem, but we really have no readily-obtainable records which allow us to evaluate whether the magnitude of the problem is increasing or changing. However, we believe that there has been increased losses of 1- and 2-year-old fish due to illegal fishing. DFG wardens spend about 2,000 hours annually enforcing striped bass regulations in the Bay Area. In fact, more than that is spent in the upper Delta and upper river system already.

This brings me to the hard part of the presentation, and that is, what can we do about all of this? Luckily, I'm short on time; so I won't be able to say much, and I'll make it brief. Before I list a few of those actions, I'd like to mention that there are no easy solutions to these problems. Easy solutions, just like good reservoir construction sites in California, are all used up. But there may be some things that could be done, and they're not all-inclusive by any means. First of all, some of the most important actions that we could take to correct the fishery resource problems in the Estuary relate to flow issues. We should first of all:

1) Encourage the SWRCB to impose stronger conditions in water rights permits;

2) Negotiate with DWR and the Bureau for operational measures and facilities to eliminate, or at least reduce, the impact of their projects. Some of these operational measures could include pumping curtailments, outflow augmentations and reduced diversions. Facilities that could be sought after would include improved fish screens at the pumping plants and better ways to move water through or around the Delta to the pumps. Alternatively, we could move the pumps. If you're reading between the lines, that sounds like the Peripheral Canal, doesn't it? In fact, it is.

Other regulatory actions could be taken by the RWQCBs or other agencies, and they include:

1) More stringent waste discharge requirements that would reduce chronic and sub-lethal biological impacts;

2) Regulations that would require dredge disposal off-shore in the deep ocean or on land as opposed to the Bay;

3) Development and implementation of stringent laws prohibiting the dumping of ballast waters in the Bay;

4) Concerted law enforcement efforts to reduce illegal take of undersized and adult fish, primarily striped bass.

Our Department's director has already requested his staff to develop recommendations for reducing the illegal take of these species.

These are only a few of the solutions. I think if some of these were implemented we would have noticeable improvements that could be made in the downward trend of our natural resources that we see in the Estuary. Thank you.

A DISCUSSION OF ISSUES RELEVANT TO THE ENTRAPMENT ZONE IN THE SAN FRANCISCO BAY ESTUARY

Working Paper
Submitted for
San Francisco Estuary Project
Technical Workshop on the Entrapment Zone

Wim Kimmerer
BioSystems Analysis, Inc.

Dave Peterson, USGS
Fred Nichols, USGS
Larry Smith, USGS
Alan Jassby, U.C. Davis
Lee Miller, CDFG

August 12, 1991

This paper introduces eight issues for consideration at the workshop. Each of the issues is discussed here by one or more of the authors listed above. The initial discussion of each issue, by Kimmerer, is based on a general review of the literature pertaining to the entrapment zone of this estuary, as well as analyses of data gathered in the monitoring programs of the Interagency Ecological Studies Program. Further discussion of some of the issues was prepared by the other authors listed above. In writing these responses all authors have assumed that readers are familiar with the estuary and with basic terminology of estuarine physics and biology.

The eight issues to be discussed are:

1. **What is the physical, chemical, and biological definition of the EZ in the San Francisco Bay estuary?**

2. **What components of the estuarine ecosystem (i.e. species, food web, or habitat) are significantly affected by processes occurring in the EZ?**

3. **To what extent are particles and populations concentrated by gravitational circulation, and to what extent by other physical processes such as exchange between shoals and channels coupled with wind-driven resuspension?**

4. **To what extent is the concentration of biota in the EZ caused by physics, and to what extent by biology, e.g. altered growth rate within the EZ, trophic interactions, or behavior?**

5. **How do location and the timing and extent of movement of the EZ affect ecosystem components?**

6. **Do any effects of position of the EZ occur because of topography, or through correlates of EZ position, e.g. freshwater flow, entrainment, or inputs of nutrients or organic matter?**

7. **How can measurements of salinity or electrical specific conductance be used as an index of EZ position? Are better indices or measurements available?**

8. **To what extent can the EZ be positioned by different freshwater flow scenarios?**

1. What is the physical, chemical, and biological definition of the EZ in the San Francisco Bay estuary?

The entrapment zone is a region of the estuary in which particles and organisms are trapped by the interaction of their settling with current shear. The description of entrapment appearing in most of the literature on the topic[1] can be summarized as follows: a gradient in water surface elevation causes surface freshwater to flow downstream over a layer of saltier water. Turbulent mixing across the interface entrains salt water from the deep layer into the surface layer. The horizontal salinity gradient causes an inward flow at depth, which supplies the salt water to be entrained. An upward flow is assumed to occur between the two layers. Particles or organisms that sink or swim out of the surface layer are entrained in the upstream and upward flows, becoming trapped in this part of the estuary.

Although the description above is a useful conceptual model of entrapment, it ignores several effects that are probably important in San Francisco Bay. The upward flow is calculated from continuity, not generally measured. It is embedded in a shear layer in which typical vertical turbulent velocities may be much larger than this calculated flow.

Another problem with this description is that tidal velocities often far exceed the flow velocity of the surface freshwater layer or the deep saline layer. Instead of a two-layer flow, one more often sees unidirectional flow on each tide, with an asymmetry between ebb and flood current profiles: on the flood, flow velocity is relatively greater at depth, while on the ebb it is relatively greater near the surface. The ebb-flood asymmetry is produced by the horizontal gradients in surface elevation and density; that is, gravitational circulation reinforces the flood near the bottom and the ebb at the surface. Net transport, obtained by integrating velocity profiles over depth ranges and over a tidal cycle, is upstream at depth and out at the surface; however, measuring this net transport can be difficult because the net velocities are a small fraction of the instantaneous velocities. However, this net transport still results in entrapment of particles.

A third problem is that turbidity maxima can occur through other mechanisms (see Issue #3).

Particles of organic or inorganic material as well as phytoplankton and zooplankton can become locally concentrated by the above mechanism if their settling rates are sufficient to remove them from the surface layer. Organisms that swim may migrate vertically to maintain position through interaction with net two-layer flow, producing a local concentration as with settling particles[2]. Different particle settling velocities or organism swimming behavior would result in different locations of the maximum.

Although particles and organisms are concentrated in the EZ, growth rates of organisms may not be enhanced there (See Issue 4). Also, the EZ represents a rather small part of the total volume of the estuary, so elevated production there may represent a small part of total system production.

D. Peterson

A. What is the physical definition..?

The seaward limb of the EZ is the gravitational circulation cell (or cells). To this end the impressive drifter experiments of Conomos provide a gross overview of the mean current structure. As a first approximation in constructing this, note that bottom drifters are entrained and transported into the bay from 25 km offshore and beyond.

Question #1. What role, if any, do tidal currents play in this offshore regime of near-bottom landward flow into the Bay?

Marlene Noble, for example, feels most if not all of this flow is associated with gravitational circulation but a tidal contribution cannot be ruled out.

As an aside, it is interesting Garvine (1991) seems surprised (?) impressed (?) that the mean near-bottom landward flow off of the mouth of the Delaware estuary is relatively strong and extends at least 40 km offshore for an estuary/shelf system with weak vertical stratification.

Assuming the above mentioned drifter experiments offer some 3-dimensional insight, note a second feature, the San Pablo Bay (shoreline) convergence of bottom drifters (Figure from Conomos enclosed).

<u>Question</u> <u>#2.</u> What does this shoreline convergence mean?

Given the scanty (in time and space) field observations with instruments, who knows or can explain it in a convincing way? And, if field observations are lacking in detail, are there any helpful results from numerical simulation experiments? Festa and Hansen's paper from the past (1976) is at the very least helpful in indicating the complexity of the problem. Their paper is entitled "A two-dimensional numerical model of estuarine circulation: the effects of altering depth and river discharge." Perhaps not fully appreciated in estuarine literature is how sensitive their model results are to very small changes in channel depth (their Fig. 12). Given that I'm not knowledgeable about numerical simulation experiments of estuarine dynamics, I am not aware if researchers have sorted out what a 3-D channel/shoal response might look like (e.g., Festa & Hansen are 2-D, the drifters trajectories dropped into channels [at the surface and at depth] and subsequently washed up on the shoreline are roughly 3-D). The point I'm trying to make here is that the bay has a weird geometry and given that physical oceanographers know geometry is very important in developing, modifying and maintaining complex circulation patterns and structures that are not yet completely understood (or at least not yet completely documented) and given the sparse observations, it is difficult to develop hard information on the Bay's physics.

<u>Question</u> <u>#3.</u> Given the above can the circulation in the bay <u>ever</u> be adequately

documented or known given, as you discussed, the complexity of the problem?

Marlene Noble suggested a relatively tight spacing of upward scanning acoustic doppler current meters (for example, roughly a dozen or so across the Chipps Island section) probably has the temporal/spatial resolution to extract the 3-D circulation structure from background noise for tidal and subtidal frequencies given full exposure to tidal, river flow and wind events and regimes. In effect many dozens of instruments would be used if the entire northern reach were studied simultaneously. Of course more realistically such instruments will be used in smaller numbers (and are being used), which ultimately will advance our understanding of the Bay's physics.

<u>Question</u> <u>#4.</u> If the EZ concept does in fact have useful management implications what about its historical perspective, is this relevant and can it ever be known?

For example, to the extent the "position" of the EZ is related to the question of salt penetration, does the salt field change significantly in the bay with channelization? It is my understanding most of the channelization took place well before the 1920's whereas salinity observations were made after this period.

B. <u>What is the chemical definition</u>..?

In the summer/fall of most wet-intermediate-dry years (but not <u>very</u> <u>dry</u> years) the dissolved inorganic nutrient distributions in northern San Francisco bay show a minimum in concentrations when plotted with salinity in the region of the chlorophyll (phytoplankton) and turbidity maximum in Suisun Bay. This indicates the dynamics between photic and aphotic processes are shifted towards photic processes and, generally, dissolved oxygen and pH distributions support this interpretation. As you have discussed the chlorophyll and turbidity maximum may or may not be associated with the physics of the EZ but you suspect that the turbidity maximum is most simply explained by gravitational circulation and it is even less clear what role gravitational circulation may play in maintaining the chlorophyll maximum (see also attached from Peterson and others, 1989).

C. What is the biological definition?

Question #5. What controls phytoplankton dynamics in San Pablo Bay?

I don't know and until this is clearly known it seems hard to comment on this question. I'm not familiar with the zooplankton observations you referred to. As you know zooplankton studies from other estuaries have inferred some of the classic examples of the importance of estuarine-type circulation on larval and fish egg transport and development.

A. Jassby

Among the many issues regarding the entrapment zone is its effect on the supply of organic carbon/energy for fueling the San Francisco Bay food web. The purpose of this working paper is to summarize information on the organic carbon budget of the Bay pertinent to the role of the entrapment zone.

1. Phytoplankton productivity in the channel is reduced by the presence of an entrapment zone. Net water column productivity for channel and shoals in 1980 can be estimated using morphometric data[3], 14C uptake measurements[4], and typical assumptions about respiratory losses[5] (Table 1).

In Suisun Bay, net productivity in the channel is negative because of the small photic depth:channel depth ratio. As net photic zone productivity ($M\ L^{-2}\ T^{-1}$) and respiration ($M\ L^{-3}\ T^{-1}$) are roughly proportional to biomass in the Bay, the effect of increased biomass is simply to lower net productivity in the channel, i.e., to make it even more negative. The presence of an entrapment zone therefore should decrease channel productivity.

2. Shoal areas and the subembayment as a whole do have enhanced phytoplankton

productivity when an entrapment zone is present. If the presence of an entrapment zone increases the biomass in shoal areas, then their productivity, which is typically positive, will be enhanced. So an entrapment zone has opposite effects on channel and shoal productivity. As shoal productivity is dominant, the net effect is to increase subembayment productivity. The increases can be substantial, as they are essentially proportional to biomass.

3. The enhanced primary productivity due to the presence of an entrapment zone, however, may have little effect on the overall supply of organic carbon. An inventory of organic carbon sources for Suisun Bay in 1980 suggests that primary productivity typically plays a minor role[5] (Table 2). The dominant source appears to have been organic carbon from Delta discharge, even when only 10% is considered to have been available for further consumption. POC constituted at least 10% of riverine TOC, and most of the POC was due to riverine phytoplankton or phytoplankton-derived detritus. Tidal marsh export of organic carbon also may be a larger organic carbon source than phytoplankton productivity, especially considering the large numbers of waterfowl in Suisun Marsh and the practice of flushing waterfowl ponds.

Two additional pieces of evidence suggest phytoplankton productivity is secondary: Stable isotope results indicate that much of the POC in the entrapment zone may at times be of riverine origin[6], and bacterioplankton productivity can greatly exceed phytoplankton productivity[7]. So variations in phytoplankton productivity due to positioning of the entrapment zone may not be ecologically important. Stated another way, the entrapment zone position may have little effect on the overall magnitude of organic carbon sources.

4. As far as the supply of organic carbon to the food web is concerned, the effect of entrapment on residence time of food particles is more important than the effect on primary productivity. Particles with certain characteristics, including those capable of entering the food web, have a higher residence time in a given region when an entrapment zone is present. This applies to particles from upstream and from tidal marsh export, as much as

to locally-produced phytoplankton. There are two main consequences. First, the longer particles reside in a given region, the more chance they have of contributing to the food web in that region. Second, even though the production of POC may not be enhanced, its loss is retarded and biomass accumulates compared to non-EZ conditions. As a result of these factors, the flow from organic carbon sources into the food web must be relatively high in the entrapment zone.

5. Because the overall carbon supply is not significantly enhanced by the EZ, increased consumption of particles in the EZ may be at the expense of downstream food webs. Organic carbon sources for the northern reach (i.e., from Golden Gate to Chipps Island) totalled 1.1 x 10^{11} g C yr^{-1} in 1980[3]. If we assume a $C:0_2$ ratio of 1, which appears to be the mean ratio for benthic respiration in the Bay[8], then these sources should give rise to an oxygen consumption of 2.9 x 10^{11} g C yr^{-1}. In comparison, Peterson[9] estimated a substrate oxygen consumption of 2.3 x 10^{11} g C yr^{-1} for the northern reach based on a mass balance for oxygen. The correspondence is remarkably close, perhaps to close given that (O_2 consumption):(C source) ratios are much lower in most estuaries. If the results are too be believed, however, they imply that most of what comes *into* the northern reach is consumed *within* the northern reach. If material is not trapped within Suisun Bay, then, perhaps it enters the food web downstream before the Golden Gate. The entrapment zone may be robbing Paul (San Pablo) just to pay Peter. The entrapment zone thus results in a spatial redistribution, but not an increase, of food sources within the Bay.

F. Nichols

Benthic invertebrate larvae can also be transported up estuary to the EZ in bottom currents driven by tidal flows and gravitational circulation (Questions 2, 4-6).

L. Smith

Definitions. I prefer to use the terms null zone and high turbidity zone instead of the term entrapment zone, which your answer to question 1 suggests is ambiguous. The null zone is defined to be the most landward extent of gravitational circulation in the bay as defined by low-pass filtered current measurements. It is a zone instead of a location because several factors make precise location impossible. These factors include local bathymetry, variations in the tides and wind, small variations in freshwater inflow, and measurement limitations of current meters.

A high turbidity zone, however, can be defined by averaging measurements of suspended particulate matter (SPM) over the water column. Such a zone is likely to have multiple longitudinal maxima because of the variety of mechanisms that affect SPM concentrations. Secchi-disc measurements may not be adequate to define high-turbidity zones in northern SF Bay because surface SPM concentrations may correlate poorly with concentrations elsewhere in the water column.

A zone of high phytoplankton concentration corresponds well to a high turbidity zone whenever particle sources, sinks, and densities are similar. I don't know how significantly these whenevers are violated in northern SF Bay, but I suspect that that zones of high turbidity and high chlorophyll overlap. I would also suspect that zooplankton and larval fish maxima would roughly correspond to these same zones because they have evolved mechanisms to make it so.

2. What components of the estuarine ecosystem (i.e. species, food web, or habitat) are significantly affected by processes occurring in the EZ?

There are two parts to this question: first, what components are affected by the presence of an EZ, and second, what components are affected by its position. The second question is discussed in Issue 5. All species found commonly within the EZ are probably affected by its presence. For example, some phytoplankton are concentrated there but growth rates may be reduced by the high turbidity[10]. Phytoplankton species concentrated include several common estuarine diatoms such as *Skeletonema* spp. and *Thalassiosira* spp[1]. Zooplankton of certain species are concentrated there, including the copepod *Eurytemora affinis*, the mysid shrimp *Neomysis mercedis*, and several other taxa[11]. Early life stages of fish including delta smelt[12] and striped bass[13] appear to be most abundant in the vicinity of the EZ.

The principal species mentioned above form a subset of the food web of the entrapment zone: *E. affinis* feeds on diatoms, *N. mercedis* on diatoms and on *E. affinis*, and striped bass larvae and delta smelt on zooplankton. It is therefore tempting to consider the concentration maximum in these species as a trophic effect. However, limited evidence suggests that the enhanced food supply in the EZ may not result in enhanced feeding for some species (See Issue 4); i.e. there may be little or no trophic advantage for organisms to be in the EZ. Thus the effect of the EZ on the food web appears to be limited to the enhanced concentration of organisms.

Any selective advantage conferred by accumulation in the EZ is apparently not related to feeding. Alternative advantages include predator avoidance and avoidance of transport out of the system. Predator avoidance appears to be an unlikely advantage of EZ residence since the predators reside there too. However, it would be very advantageous for organisms to avoid being washed out of the estuary. Since the EZ organisms listed above have at most limited swimming ability, they must either have population turnover times that are short relative to residence time of the water[14], or they must use circulation to increase their residence time relative to that of the water. Using vertical positioning within the EZ is one way to do this. Thus, the EZ can be seen as habitat for species that are capable of exploiting this feature of the estuary.

For at least some EZ species, the EZ represents qualitatively different habitat from other areas. *E. affinis* is most abundant in a salinity range of 1-6, and its abundance declines sharply at higher salinities (Figure 1). However, this species is known to have a broad tolerance to salinity from nearly 0 to about 20, with an optimum at 12[15]. Its low abundance outside the EZ is therefore a result either of predation or of transport back into the EZ. There is no evidence that the abundance or activity of predators is higher outside than inside the EZ, and several species of planktivorous fish are more abundant in the EZ.

Bacteria appear not to be particularly affected by EZ processes[16]. The importance of the EZ to microzooplankton other than copepods and rotifers is also unknown, since none of the sampling programs includes these organisms.

D. Peterson

As you probably know a very rough estimate of the importance of gravitational circulation in maintaining the salt balance in the Bay is one third gravitational circulation and two thirds eddy diffusion. To my knowledge no such estimates have ever been made for particles, but one might assume gravitational circulation plays a stronger role in particle transport than for dissolved salts. Of course tidal climate clearly plays a very important role in the ultimate disposition of sediments. I'm not convinced, however, that the unusually high efficiency of trapping sediments in the Mare Island or the Napa River tributary estuary is adequately explained by tidal phenomena (as the Scripps Institution of Oceanography coastal engineers seem to believe). In brief, in my opinion essentially zero is known about this topic in the Bay. For purposes of discussion two useful views of this topic include the 1970's paper by Festa and Hansen (a gravitational circulation control) and 1980's paper by Uncles (a tidal/river-flow control). But before attempting to hypothesize about this question a comprehensive overview of sediment dynamics and budgets in the Bay from a long term perspective would be useful.

F. Nichols

In late summer, immediately following the summer phytoplankton maximum in water column of the EZ and coincident with a period of reduced ebb tidal velocities, a large proportion of the phytoplankton cells (same species as previously dominant in the water column) settle to the bottom (Nichols and Thompson 1985 -Hydrobiologia). There is insufficient data to determine the ecological importance of this reservoir of organic matter at the bottom, how the amount accumulated during any year is determined by hydrodynamic processes (river flow), or the eventual fate of these deposited cells (e.g., resuspension and transport versus burial).

The benthos of the EZ, particularly in Suisun Bay, is strongly determined by hydrodynamic processes occurring in the EZ. Benthic invertebrate species composition and abundance, for example, are determined by seasonal and interannual patterns in river flow which, in turn, determine (through gravitational circulation) the transport of larvae and juveniles in bottom currents. During periods of high river inflow, the benthos consists of a few fresh- and brackish-water species because most estuarine species are intolerant of alternating periods of inundation by fresh and salt water. During prolonged dry periods (>16 months) when river flows remain below 1000 m /s and salt content remains high (>5 o/oo), large numbers of estuarine (salt dependent) species are able to penetrate the barrier of Carquinez Strait (see Issue 6) and become established in the Suisun Bay region (Nichols et al., 1990). Presumably, larvae (and perhaps juveniles) are involuntarily transported upstream from established adult populations in San Pablo Bay.

3. To what extent are particles and populations concentrated by gravitational circulation, and to what extent by other physical processes such as exchange between shoals and channels coupled with wind-driven resuspension?

A number of physical processes other than gravitational circulation can be important in concentrating particles and organisms. All seem to depend on interactions between variations in velocity and settling of particles or swimming behavior of organisms.

In most estuaries including the San Francisco Bay estuary, the cross-sectional area generally increases in a downstream direction[17]. River flow velocity averaged across the estuary is lower where the cross-sectional area is larger. In addition, tidal currents generally decrease from the mouth of the estuary to some upstream point where they vanish. The combined tidal and river velocities (mean absolute or root-mean-square) therefore have a minimum at some intermediate point. This minimum results in settlement of particles during slack water and subsequent resuspension during tidal flows, causing a turbidity maximum near the area of minimum current velocities.

Lateral variation can also concentrate particles or organisms. Tidal exchange between channels and shoals, particularly under windy conditions, can produce local maxima in turbidity and perhaps phytoplankton. Local maxima in abundance of zooplankton and presumably other organisms can occur associated with recurring tidal eddies or with sills[18].

I believe that in the San Francisco Bay estuary the dominant means of producing maxima in zooplankton, chlorophyll, some phytoplankton species, and turbidity is in fact gravitational circulation, although these other mechanisms may be important at some times and places. The position of the turbidity maximum maintains a fairly monotonic relationship (with some variation) with the position of a given surface salinity value (Figure 2). The peak value of *E. affinis* also occurs at around the same salinity in each month. If different mechanisms were concentrating these components at different flows, one would expect to see the peaks occur at different salinity values.

L. Smith

Mechanisms for creating a high turbidity zone. The often-repeated explanation for an observed high turbidity zone in northern SF Bay is the interaction of delta-derived particles with the null zone, as you have described. This explanation suggests that the high turbidity zone should overlap the null zone. It ignores, however, other published concepts of northern SF Bay.

A first approximation of the seaward mixing of land-derived particles is the seaward mixing of fresh water. Fischer and Dudley (1975) and Conomos (1979) suggest that the summer salt balance in the northern reach, or the mean mixing of fresh water seaward, can be maintained almost entirely by processes other than gravitational circulation. If they are correct, then the physical mixing of particles in the northern reach might be dominated by these other processes.

Fischer and Dudley call these other processes tidal pumping and trapping. Tidal pumping refers to the horizontal asymmetry of tidal and net currents that leads to lateral and longitudinal exchanges among water masses. Tidal trapping refers to the isolation of a water mass in an off-channel area during part of the tidal cycle and subsequent release of the mass later. Although pumping and trapping mechanisms are not entirely distinct, together they can effectively increase the net (tidally averaged) longitudinal diffusion of a water mass, lengthening the time that some water takes to move through the bay.

If an off-channel area is shallow, its currents are significantly smaller than those of the channels, and negatively buoyant particles tend to settle to the bottom, further lengthening their residence times in the bay. This increased residence time, coupled with wind-wave generated resuspension of sediments in the shallows can lead to the accumulation of particles in channels adjacent to large, off-channel areas. The large amount of maintenance dredging done in Mare Island Strait might be explained as settling of trapped sediment without wind-generated resuspension.

Another concept that departs from the usual explanation is Ray Krone's seasonal sediment movement concept. His idea is that the source of SPM for the summer high turbidity zone is San Pablo Bay rather than the delta. He hypothesizes settling of delta-derived particles in the shallows of San Pablo Bay during winter runoff events, followed by wind resuspension during the summer. Those sediments that exchange into the channels sink toward the bottom and are subsequently carried landward to the null zone by gravitational circulation. I am unaware of a dataset, other than collected for his thesis, that confirms or denies his concept. However, this concept would make separate the summer sources of SPM and chlorophyll in the area of the null zone.

4. To what extent is the concentration of biota in the EZ caused by physics, and to what extent by biology, e.g. altered growth rate within the EZ, trophic interactions, or behavior?

Particles concentrated in the EZ have settling rates sufficient on average to remove them from the surface layer but not enough to remove them from the water column. Concentration of biota in the EZ is complicated by growth and mortality as well as behavior.

Phytoplankton are apparently concentrated in the EZ by settling as for inert particles, although settling rates may be enhanced through flocculation[1]. Growth is generally light limited in this part of the estuary, so net growth in the channels may be lower than that in shallow areas[3]. However, tidal exchange between the shoals and channels may enhance production for the system as a whole, since growth rates are higher in shoals.

There is little evidence that growth of the zooplankton is food-limited, although considerably more work needs to be done[19]. If they are not limited by food, there is no reason to expect zooplankton growth or development rates to be higher in the EZ than out.

The question of food limitation in striped bass larvae is also still open, although they are never classified as starved, according to histological and morphological characters[20]. Growth rates are variable between years[21], and the variation is consistent with a hypothesis that reduced growth is caused by low food concentrations, but alternative explanations cannot be ruled out. Furthermore, there is no evidence that growth rates or feeding rates are enhanced in the EZ relative to other locations in a given year.

If growth rates (and therefore trophic interactions) of zooplankton and striped bass larvae are not higher within the EZ, then their behavior may be the principal mechanism for concentration. Specifically, organisms that swim downward, or that migrate vertically on a tidal cycle, can avoid being washed out of the estuary, thereby becoming concentrated. This is a common behavioral pattern in estuarine organisms. In the San Francisco Bay estuary, some zooplankton including *N. mercedis*[2] and possibly *E. affinis*[22] avoid the surface waters or migrate on a tidal cycle. Striped bass eggs and larvae occupy progressively deeper strata during early development, which should concentrate them in the EZ[23].

Freshwater zooplankton species presumably arrive in the estuary by transport from reservoirs. They are unlikely to have the behavioral mechanism to remain in the estuary, since there is no selective pressure to do so. Their abundances generally decline monotonically with salinity, implying that they are not being concentrated within the EZ[24]. The lack of abundance peak may imply a lack of behavioral mechanism for position maintenance, or it salinity stress may prevent such a response.

To summarize, there is no evidence that the growth or mortality rates of any species are altered in the EZ relative to other locations. Since motile organisms do not generally sink passively, behavior may be the only means for them to become concentrated.

F. Nichols

The issue of different growth rates inside the EZ is not necessarily covered in the term "concentration of biota". There is some evidence, from a two-year study of growth of the clam *Macoma balthica* at four locations around the bay, that proximity to the EZ may be a factor in increased clam growth rates. The clams at an intertidal site in Southhampton Bay (off Carquinez Strait) grew much faster and achieved a maximum size that was much greater than at intertidal sites elsewhere in the bay (Thompson and Nichols 1988). The timing and magnitude of growth rates appeared related to the seasonal maxima in pelagic and benthic diatoms in the vicinity.

L. Miller

My response to question 4 is mainly a discussion of striped bass and what we know about their relationship to the EZ. Striped bass eggs are spawned and hatch in freshwater. Spawning occurs mostly above Sacramento on the Sacramento River. The eggs hatch en route to the estuary, a distance of about 160 km. Eggs and larvae spawned on the San Joaquin River are located on the order of 15-25 km above the EZ. The larvae from both areas move seaward with freshwater flows, tending to accumulate upstream of the EZ. In most years San Joaquin River inflow is low relative to the inflow from the Sacramento River but the San Joaquin River eggs and larva are kept in suspension by tidal currents.

The EZ was initially defined in terms of specific electrical conductance (EC) as the segment of the estuary between 2 mS/cm and 10 mS/cm[1]. However we recognize this to be an approximate definition and we are still in the process of defining it as per Wim's comments. I have used a surface measurement of 1 mS/cm EC as an upstream limit and 10 mS/cm as the downstream limit. Based on this definition we find the highest concentrations of the early stages of bass, 6 mm to 14 mm long, located upstream of the EZ in the EC range of 0.500-0.999 mS/cm, a transition area from fresh water to salt water (Figure 2a). This raises the question of whether entrapment is occurring upstream of where we think it occurs, or at least upstream of where I conveniently defined the EZ, or whether something else is happening? We will need to explore this with analyses of data from additional years.

The proportion of the larval striped bass population in the EZ, as defined here, is small but tends to increase with size. Bass are free swimming and at a length of 8 mm to 9 mm they can evade sampling gear and probably can control their location. They could remain in fresh water or presumably move even downstream of the EZ since salinity should not be a barrier. Striped bass larvae survive best in the laboratory at 10.5 ppt. (Bayless 1972, cited in Setzler et al. 1980) which is approximately an EC of 17 mS/cm. Even 9 day old striped bass larva, which are about 6 mm, have optimal survival at salinities of 6.75 ppt (Lal et al, 1977 cited in Setzler, et al. 1980) which is comparable to an EC of roughly 11 mS/cm.

Wim's suggestion that accumulation in or near the EZ is due to their behavior coupled with the physical process of entrapment appears to be what is occurring. The early development of a swim bladder and a mid-depth to bottom orientation in the EZ (Fujimura,1991) suggests a behavioral capability to control their vertical distribution. Settling out to the mid-depth to bottom would result in their accumulation in or near the EZ rather than moving further seaward in the surface flow. Such behavior has likely evolved as a survival strategy for retention in the estuarine environment where higher turbidity as well as higher food concentration favor survival compared with the marine environment. Two important food sources, Neomysis and Eurytemora, were historically more concentrated in the brackish environment in this estuary as well as in estuaries to which striped bass are native.

The accumulation of bass near in the EZ during spring and early summer could be independent of entrapment or their settling out behavior but reflect better feeding conditions which enhances survival in the EZ relative to survival at other locations. We cannot readily compare the survival of young bass in the EZ with survival in other areas because immigration into the EZ and emigration out of other areas is occurring.

We did compare growth rates of young bass less than 14 mm caught in the EZ with growth rates of young bass from upstream of the EZ using otolith data for 1984 and 1988. The results did not demonstrate greater growth for larvae captured in the EZ. Thus bass appear to have no growth or survival advantage related to more food in the EZ when compared to the upstream areas. However they are much less subject to entrainment in Delta water exports by being further downstream.

The advantages of being in the EZ may be greater for young bass after the larval stages when they switch to Neomysis and larger shrimp. I hope to present results from analyses currently underway which may help shed light on the use of the EZ by post larval stages.

In this estuary young bass abundance at the 38 mm size is strongly correlated with Delta outflow and Delta diversions, a response not clearly demonstrated for other striped bass populations. Mechanisms hypothesized by Turner and Chadwick (1972) to explain this abundance-flow relationship are: (1) dilution of toxics by higher flows. (2) Distributing bass away from the Delta where water export entrainment losses have been identified as having major impacts on the abundance of young bass. (3) Distributing the bass to Suisun Bay where food supply conditions are enhanced by higher production in the shoals.

An ancillary hypothesis for this third mechanism is that when outflow is high two layered flow conditions are stronger. Striped bass larvae entering the estuary under high flow conditions would settle out over areas with higher average bottom salinities than would be the case when the two layered flow system is weaker under low flow conditions. This would tend to place larvae into a prey field where Eurytemora concentrations are much higher than they are in fresh water. We have seen some evidence of this in 1986 when flows were high, bass survival was high and the population was exposed to higher concentrations of Eurytemora (CDFG,1988). We have not tested growth rates in and above the EZ for 1986 but overall growth rates were higher in 1986 than in other recent years. However, freshwater food resources were also more abundant and other factors may also have contributed to the high survival in 1986.

We need to test whether or not the EZ provides a better environment with greater outflow conditions and if so why. In many estuaries there are positive correlations between fish or shrimp abundance and outflow. Such relationships in this estuary have been found for splittail, American shad, longfin smelt, starry flounder, and Crangon franciscorum, as well as striped bass. In some cases e.g., American shad, the flow effects are unlikely to be related EZ phenomenon but factors upstream. However for other cases the EZ may be important.

Since 1988, the accidental introduction of Potamocorbula amurensis has apparently been the cause of a major decline in the concentrations of Eurytemora in the EZ. However the trophic picture for striped bass is also complicated by new exotic food resources common to both freshwater and the EZ and have to some extent filled the void left by the decline of Eurytemora. We are still sorting this out.

A final observation. It is also apparent that an entrapment situation is not necessary for striped bass. Striped bass are an estuarine species but there are freshwater populations that are sustained in the Santee-Cooper system and the Colorado River without an EZ. However a similar environmental situation exists in that a lake or reservoir provides an environment were the net flow is reduced.

5. **How do location and the timing and extent of movement of the EZ affect ecosystem components?**

Depending on freshwater flow and tides, the position of the EZ can vary from the western delta nearly to the ocean[13], although it is usually found east of Carquinez Strait. There has been considerable speculation and some evidence that the position of the EZ affects biomass and productivity in the EZ. There are two aspects to this question, each of which should be considered separately. First, the volume of the EZ can vary with its longitudinal position, since the cross-sectional area changes with position[13]. At a given abundance or biomass (i.e. per unit volume), the total population size varies with the volume of habitat. Second, the abundance or biomass can vary within the EZ. These two effects could be related, in that a smaller habitat could increase losses to mixing out of the population center, resulting in a lower abundance in the population center.

When the EZ is upstream of the confluence of the two rivers, its volume is considerably less than when it is in Suisun Bay (Figure 3). This effect has been implicated in the reduced population size of *N. mercedis*[25].

A convincing argument has been made that dependence of phytoplankton biomass on EZ position is a result of exchange between shallows and channel waters[1,4]. According to this model the combination of enhanced growth in the shallows with entrapment in the channel results in higher biomass when the EZ is in Suisun Bay compared to when it is in the delta. A similar mechanism has been suggested for delta smelt, although the only evidence to support this is higher abundance in shallow waters than deep[8].

The size of the *N. mercedis* population depends on EZ position through habitat volume[18], but also through changes in abundance[26]. In the fall and perhaps in the spring, the abundance of *E. affinis* is higher when the EZ is in an intermediate position, and lowest when it is in the delta[27]. The mechanism for this is unclear, since zooplankton generally are less abundant in shallow water and, since they are less abundant in the surface layer they are less likely to be transported into the shallows. One possibility is that the complex topography in eastern Suisun and Honker bays causes eddies or other persistent circulation features that increases residence time and abundance[14].

F. Nichols

To the extent that the physical processes determining the position of the EZ (e.g., river flow) also determine the transport and final settlement of benthic invertebrate larvae (Question 2), the benthic community of Suisun Bay in any given year is related to the timing and position of the EZ during the previous year or so. However, it is not clear that the entrapment of invertebrate larvae by physical processes within the EZ determines the structure of the benthic community there. This has not been studied.

6. Do any effects of position of the EZ occur because of topography, or through correlates of EZ position, e.g. freshwater flow, entrainment, or inputs of nutrients or organic matter?

The effects of position of the EZ discussed in the Issue 5 depend mainly on topography, i.e. on the presence of shallow water adjacent to the EZ. Position of the EZ is confounded by several other variables. EZ position depends mainly on freshwater outflow, and is therefore related to several other effects that may be important.

The degree of stratification and presumably the strength of entrapment within the EZ presumably depends on freshwater flow, since the asymmetry of ebb and flood tides would increase as freshwater flow increases. This could result in greater trapping of some species relative to advective losses.

An upstream position of the EZ would increase vulnerability of some species to export pumping. This mechanism has been blamed for low abundances of striped bass and delta smelt in years of low freshwater outflow[8,9], although the evidence for population effects of export pumping is not complete. Export losses of *E. affinis* do not appear to be major sources of mortality[28], although abundances used in that analysis were not necessarily the same as those in the exported water.

D. Peterson

Beyond the obvious, its hard to say much toward a 3-D type question without some solid 3-D knowledge.

F. Nichols

The constriction of the estuary at Carquinez Strait represents a major barrier to benthic invertebrates, preventing upstream dispersal of species from San Pablo Bay into Suisun Bay except during prolonged dry periods. During normal or high river inflow years, the enhanced down-estuary flows through the Strait and coincident low salinities prevent benthic species resident in San Pablo from transiting the Strait and becoming established in Suisun Bay. As a result, the benthic communities of San Pablo and Suisun Bays are quite different. During prolonged periods of low flows, however, the constriction ceases to be a barrier to the upstream transport. Thus, during such dry periods (prior to the arrival of the Asian clam, *Potamocorbula amurensis*), the San Pablo and Suisun Bay benthic communities had many species in common.

The effects of the biotic barrier at Carquinez Strait confound the effort to uncover simple relationships between the position of the EZ and benthic community dynamics. To further complicate the situation, since 1987 the large population of the new clam in Suisun Bay has itself become a barrier, presumably by preying on arriving larvae.

7. How can measurements of salinity or electrical specific conductance be used as an index of EZ position? Are better indices or measurements available?

By definition the position of the EZ is the location of entrapment as defined under Issue 1. This could be determined by taking a series of vertical profiles of longitudinal net velocity; the upstream edge of the EZ would be at the null zone where net velocity at the bottom was 0. The problem with this method is that net velocities are very difficult to measure, especially when tidal flows are large. Therefore an operational definition of EZ position is needed.

Alternative operational definitions can be based on the turbidity maximum, the salinity difference between surface and bottom, and selected ranges of salinity or electrical specific conductance (EC).

The location of the turbidity maximum is the operational definition most closely related to the concept of entrapment, but there are two drawbacks to using it to define EZ position. First, other sources of elevated turbidity (See Issue 3) can confound the use of turbidity in this way. Second, this method requires that differences in turbidity among stations be determined. Since this can be a rather noisy variable, a large number of measurements must be averaged to find the maximum. This problem could be avoided by using *in situ* transmissometry or nephelometry with an on-deck readout; however, determining the location of the EZ would still require a longitudinal transect.

The salinity gradient from surface to bottom has been used to estimate EZ position by assuming that the EZ occurs where the gradient decreases to 0 in an upstream direction[5]. However, a vertical salinity gradient is not necessary to produce entrapment, since the ebb-flood asymmetry in flow velocities is produced mainly by the longitudinal salinity gradient (See Issue 1). Thus, while this measure may be useful it needs to be calibrated against other indices of EZ position.

Arthur and Ball[1] suggested using fixed values of surface EC to define the EZ. This has the advantages that it is extremely easy to measure, can be used to determine EZ position while in the field, has a historical precedent, and can be used to determine EZ position on historical data for much of which only surface EC readings were taken. However, surface EC is not simply related to EZ position (Figure 2). Stratification increases with flow, so surface EC becomes less representative of water column conditions as the EZ moves downstream. This problem could be solved through the use of EC or salinity values from the bottom or some fixed depth, although this could not be applied to the historical data.

Since many of the field teams are now equipped with CTDs, it should be possible routinely to determine salinity profiles at each station. However, relationships among all of the measures of EZ position need to be developed so that both the historical and future data can be interpreted similarly.

D. Peterson

Festa and Hansen (1976) showed it in their 2-D steady-state numerical simulation experiments (note they refer to null point not EZ). However, when asked are better measurements or indices available(?), this seems to assume the connection between salinity and circulation has been documented which it has not.

8. To what extent can the EZ be positioned by different freshwater flow scenarios?

The effect of flow on EZ position is fairly clear[13]. Further analysis using CDFG data on monthly EC values taken near high tides during April to October and DWR DAYFLOW estimates of monthly mean delta outflow give a relationship:

$$EZ = 147 - 27.5\ LOG_{10}\ Q, \quad r^2 = 0.80,$$

where Q is flow (m^3/s) and EZ represents EZ position by the operational definition of 2mS/cm specific conductance (about 1.2 salinity), in kilometers from the Golden Gate. The standard error of the estimate is ± 1.30. Presumably much of the residual variance is due to the spring-neap tidal cycle, the use of aggregated (monthly) values, the use of DAYFLOW estimates (which incorporate several untested assumptions about water consumption and distribution in the delta), and the implicit assumption of steady state.

From this relationship it can be seen that, within the range of data used, flow has a logarithmic relationship with EZ position. A change in flow by a factor of 2 would move EZ position by 8 km, with 95% confidence limits of ± 0.74 km or 9%. The differences in EZ position that have been observed (or assumed) to influence productivity or biomass in the EZ are on the order of 10-20 km. To effect movements of that magnitude, delta outflow flow would need to change from its baseline level by a factor of 2.3-5.3. It should be possible to refine these estimates further using available data, most notably the CTD profiles taken by USGS and USBR, once these data are available.

The above discussion relates operationally defined EZ position to net delta outflow, but does not consider flows within the delta or reverse net flows in the lower San Joaquin River, both of which could affect either EZ position or the apparent effects of EZ position on some of the biota. Hydrodynamic modeling or more detailed field studies are needed to provide better information on this question.

D. Peterson

Before attempting this question a more general question might be: to what extent can the salt field be positioned by different freshwater flow scenarios?

On a monthly time scale, the surface salinities near the channel sites can be estimated to roughly $\pm$ 1 salinity unit as a function of delta flow. Estimates from some near-bottom time series are also available. To the best of my knowledge time series observations from shoals are almost none to non-existent.

Given the above, then, the circulation remains to be coupled to the salt field over a wide range of time & space scales. Until this is more complete, utilizing EZ or related concepts for purposes of estuarine management seems premature.

ENDNOTES

1. e.g. Arthur, J.F. and M.D. Ball. 1980. The Significance of the Entrapment Zone Location to the Phytoplankton Standing Crop in the San Francisco Bay - Delta Estuary. U.S. Dept. of the Interior, Water and Power Resources Service. 89 pp.

2. Orsi, J.J. 1986. Hydrobiologia 137:79-87.

3. Burau, J.R., and R.T. Cheng. *A General Method for Generating Bathymetric data for hydrodynamic computer models*. Open-File Report 89-28. U.S. Geological Survey, Sacramento, Calif. (1979).

4. Cloern, J.E., B.E. Cole, R.L.J. Wong, and A.E. Alpine. 1985. Hydrobiologia 129, 153.

5. Jassby, A.D. *Status and Trends Report on Aquatic Resources. Technical Appendix. Organic Carbon Sources for the Food Web of San Francisco Bay*. Draft version. U.S. Environmental Protection Agency, San Francisco Estuary project, Oakland, Calif. (1991).

6. Spiker, E.C., and L.E. Schemel. In *San Francisco Bay: the Urbanized Estuary*, ed. T.J. Conomos, p. 195. Pacific Div., Am. Assoc. Adv. Sci., San Francisco, Calif. (1979).

7. Hollibaugh, J.T., and P.S. Wong. Unpublished MS (1989).

8. Hammond, D.E. et al. *Hydrobiologia* 129, 69.

9. Peterson, D.H. In *San Francisco Bay: the Urbanized Estuary*, ed. T.J. Conomos, p. 175. Pacific Div., Am. Assoc. Adv. Sci., San Francisco, Calif. (1979).

10. Cloern, J., A. Alpine, B. Cole, R. Wong, J. Arthur, and M. Ball. 1983. Estuar. Coast. and Shelf Sci. 16:415-429.

11. Orsi, J.J., and W. Mecum. 1986. Estuaries 9:326-339.

12. Moyle, P.B., B. Herbold, D.E. Stevens, and L.W. Miller. Life History and Status of Delta Smelt in the Sacramento - San Joaquin Estuary, California. Submitted to Trans. Am. Fish. Soc.

13. Stevens, D.E., L.W. Miller, and D.W. Kohlhorst. 1989. Where Have California's Striped Bass Gone? Bay-Delta Project, California Dept. of Fish and Game.

14. Ketchum, B.H. 1954. Ecol. 35:191-200. The turnover time of the *E. affinis* population is probably on the order of weeks to months depending on temperature. Residence time of the entire Suisun Bay in summer is on the order of a month (Walters, R.A., R.T. Cheng, and T.J. Conomos. 1985. Hydrobiologia 129:13-36). Thus the turnover time of *E. affinis* is not much less than the residence time of the portion of the estuary in which it is abundant.

15. Roddie, B., R. Leakey, and A. Berry. 1984. J. Exp. Mar. Biol. Ecol. 79:191-2

16. Hollibaugh, T. and P. Wong. 1991. Submitted.

17. Peterson, D. H., T. J. Conomos, W. W. Broenkow, and P. C. Doherty. 1975. Estuarine and Coastal Marine Science. 3:1-11.

18. Alldredge, A.L. and W.M. Hamner. 1980. Est. Coastal Mar. Sci. 10:31-37.

19. For *E. affinis*, ratios of eggs to females do not appear to be closely related to chlorophyll, nor have they declined much over the period 1980-1988, despite a large decrease in chlorophyll in 1988 (W. Kimmerer, unpubl.). A limited number of experiments in late summer 1988 (when chlorophyll was very low) showed no food limitation of reproductive rates in *E. affinis* (Kimmerer, W.J. 1991. In prep.)

20. Striped bass larvae are never classified as starved, either in or out of the EZ, according to histological and morphological characters (Bennett, W.A., D.J. Ostrach and D.E. Hinton. 1990. The Nutritional Condition of Striped Bass Larvae from the Sacramento - San Joaquin Estuary in 1988: An Evaluation of the Starvation Hypothesis Using Morphometry and Histology. Submitted to: CA Dept. of Water Resources).

21. CDFG. 1988a. Factors Affecting Striped Bass Abundance in the Sacramento - San Joaquin River System. Exhibit 25, entered by the CDFG for the State Water Resources Control Board 1987 Water Quality/Water Rights Proceeding on the San Francisco Bay/Sacramento -San Joaquin Delta. 149 pp.

22. J.J. Orsi, CDFG, unpublished data.

23. Fujimura, R.W. 1991. Draft Technical Report: Observations on Temporal and Spatial Variability of Striped Bass Eggs and Larvae and Their Food in the Sacramento - San Joaquin River System. Interagency Ecological Study Program for the Sacramento - San Joaquin Estuary.

24. Based on plots of log abundance vs. salinity: Obrebski, S., J. Orsi, and W. Kimmerer. In prep.

25. Knutson, A. C., and J. J. Orsi. 1983. Trans. Am. Fish. Soc. 112:476-485.

26. Analysis of CDFG data shows that the abundance of *N. mercedis* is highest when the EZ is out of the Delta (Kimmerer in prep.).

27. Based on CDFG data (Kimmerer in prep.).

28. Based on analysis of CDFG zooplankton data (Kimmerer in prep.). The number of copepods exported, estimated from the rate of export pumping times the abundance at sampling stations in Old and Middle Rivers, averaged 0.06%/d (median) of the total population estimated by summing abundances in selected salinity classes times water volume in each class. Even in periods of upstream EZ position this fraction was less than 0.02%/d.

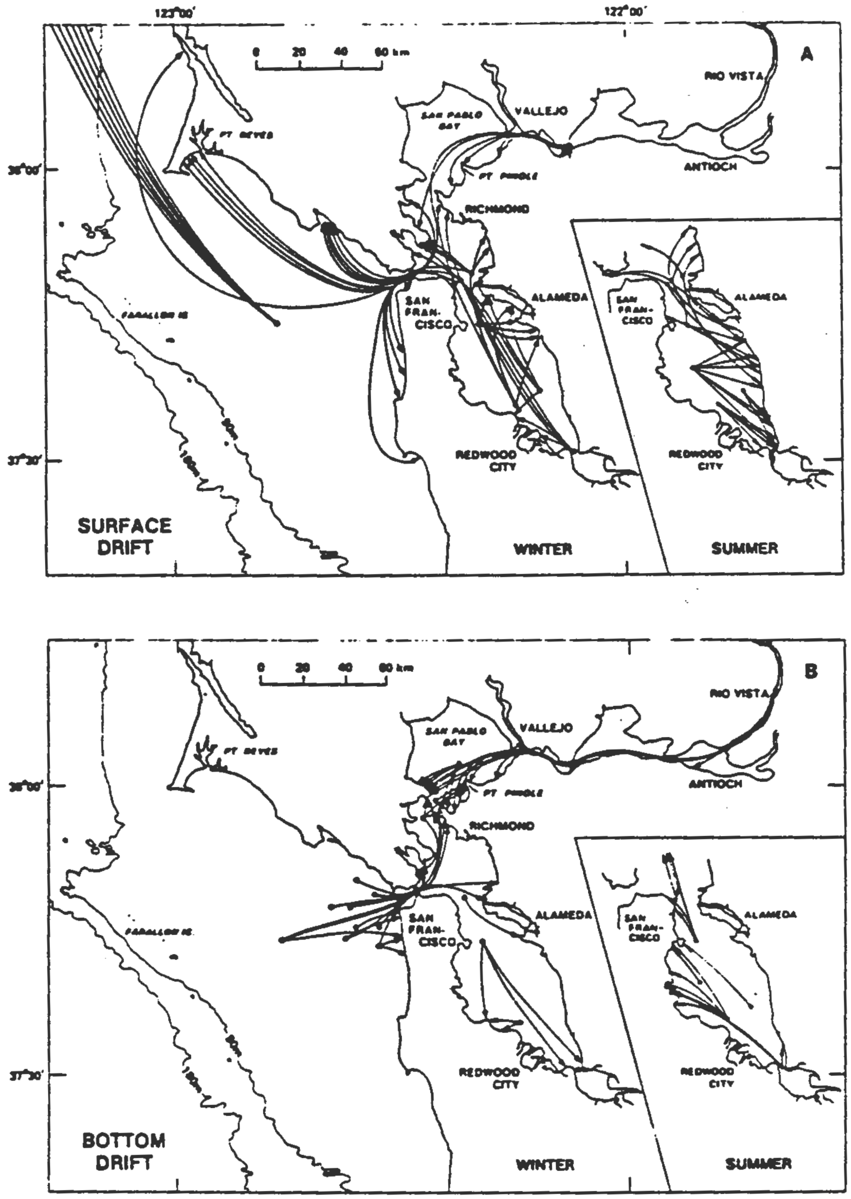


Figure 5. Release and recovery points for surface (A) and seabed (B) drifters in the bay and adjacent ocean. Drifter movements are shown as arrows drawn from release points to recovery locations and portray simplified paths of movement occurring within 2 months of release. Winter release: December 1970 (modified from 3). Summer release (southern reach only shown as inset): September 1971. Data are typical of 18 releases over a 3-year period (1970-1973).

Figure from Conomos & Peterson 1977.

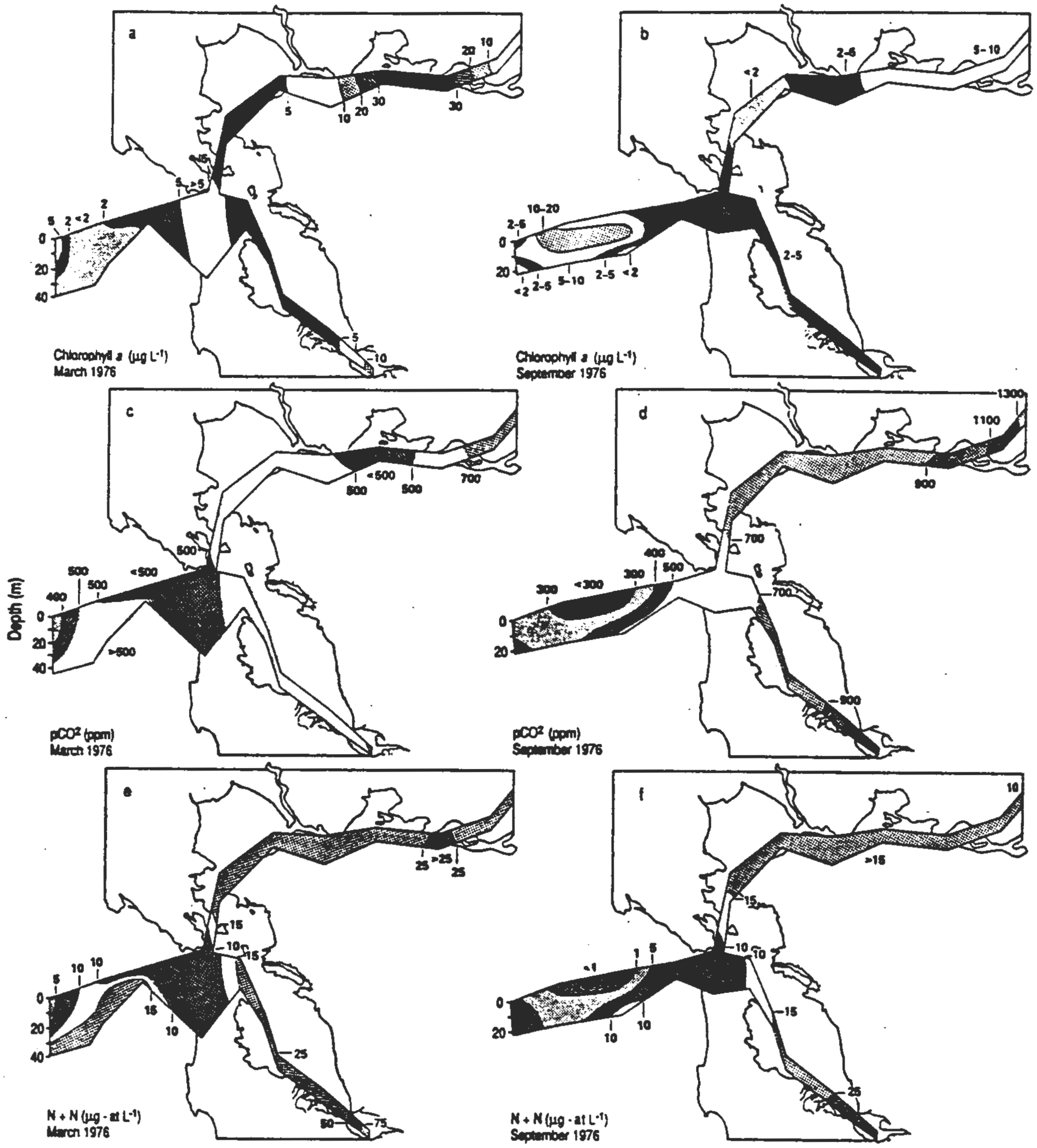


Fig. 19. Distribution of chlorophyll (panels a, b), partial pressure of carbon dioxide (panels c, d) and dissolved nitrate, plus nitrite (panels e, f) in the San Francisco Bay estuary during March and September 1976.

are typically aphotic because mean water column light is too low to sustain net photosynthesis.

The second hypothesis attributes low phytoplankton biomass to benthic filter-filtering invertebrates [Nichols, 1985]. In dry years such as 1961, 1976 and 1977, 1981, and 1985 benthic invertebrate populations increased in Suisun Bay in response to persistently elevated salinity (Nichols, 1985 and unpublished). If the increased filter-feeding invertebrate populations were responsible for the reduction in phytoplankton biomass, it follows that DSA would be anomalous in these years. The DSA pattern in midsummer 1961 was an exception. During that summer DSA behaved as expected for a normal summer, whereas during the other very dry years it did not. During 1961 the pattern of dissolved silica and other plant nutrients and the partial pressure of dissolved carbon dioxide (reflected in high pH measurements) all showed a very strong effect of phytoplankton photosynthesis into July, but not in the later surveys of September and November (see field and numerical simulation results in Figure 8 and compare with Figure 19).

We interpret the sequence of field observations from summer 1961 to winter 1962 as follows. Following the decline in summer delta flows, salinity near Pittsburg increased to over 10 parts per thousand in July. Numerical abundance of benthic invertebrates (e.g., the filter-feeding clam *Mya arenaria*) did not increase markedly, however, until September [Storrs et al., 1963]. After this increase in benthic invertebrate abundance the photic phytoplankton-dominated estuarine biochemistry apparently shifted to an aphotic (benthic invertebrate) dominated estuarine biochemistry, as reflected in decreased dissolved oxygen saturation, pH, and phytoplankton abundance, and in increased plant nutrient concentrations (cf., Figure 8 for pH changes). Inevitably, winter peak flows returned (February 1962) and salinity decreased sharply. Because the benthic invertebrates could not survive in low salinity water, their abundance declined sharply as well. Thus by the summer of 1962, the system apparently had returned to a more phytoplankton-dominated biochemistry.

Figure 1. Geometric mean and 95% confidence limits for *Eurytemora affinis.* Means determined by salinity class, then referred to mean salinity in the class.

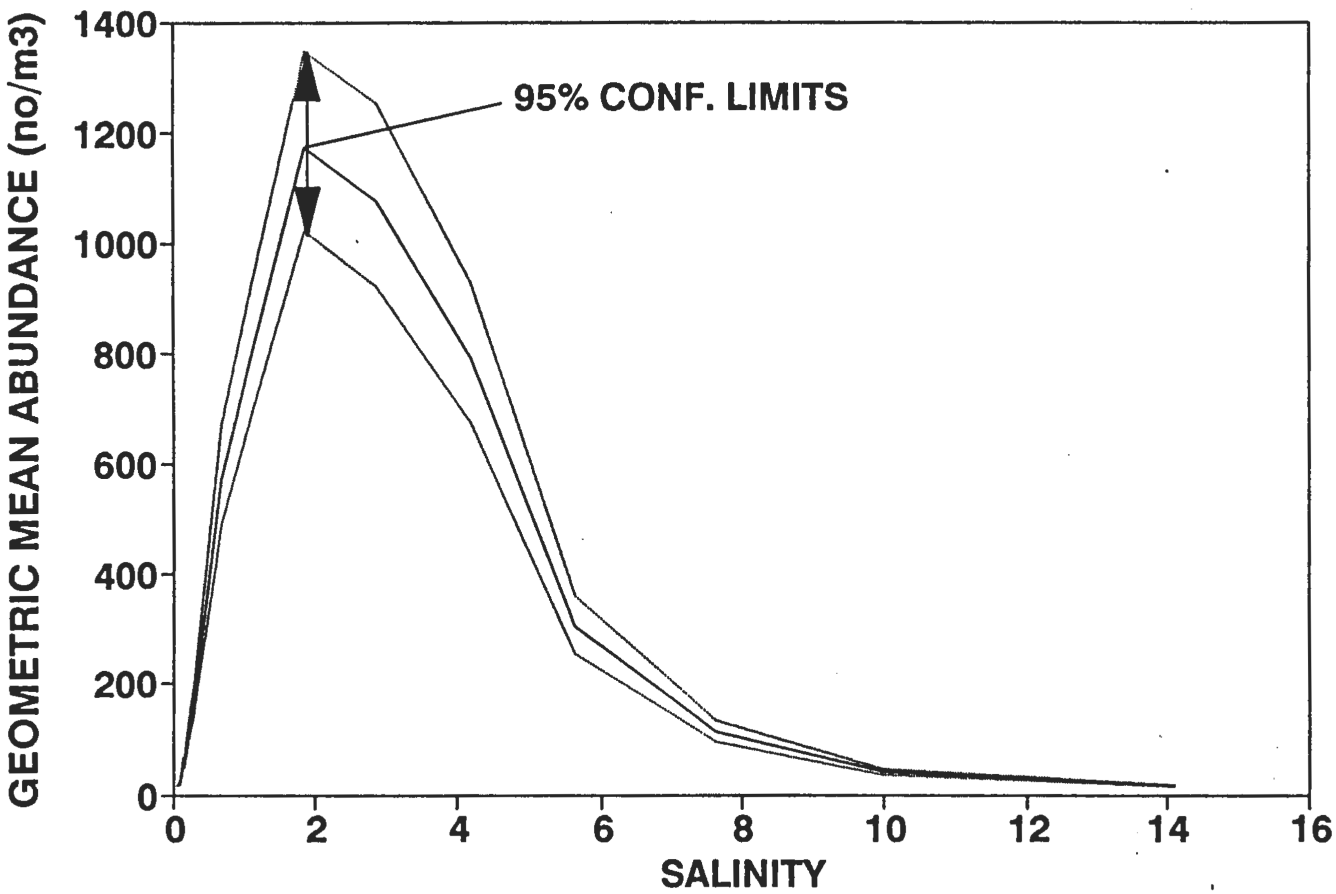


Figure 2. Distance from the Golden Gate at which EC=2 mS/cm vs. distance of minimum in monthly Secchi depth, from CDFG data.

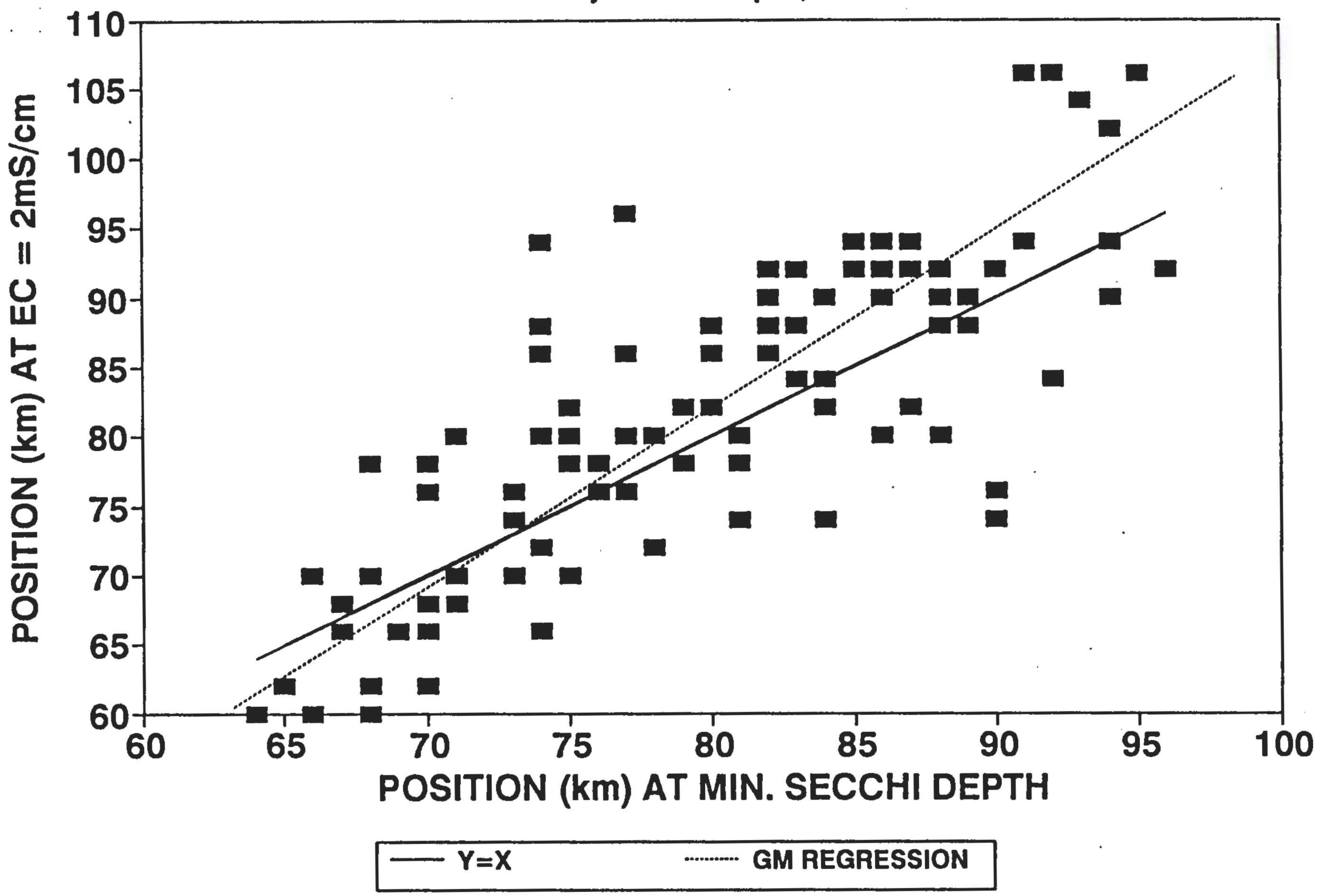
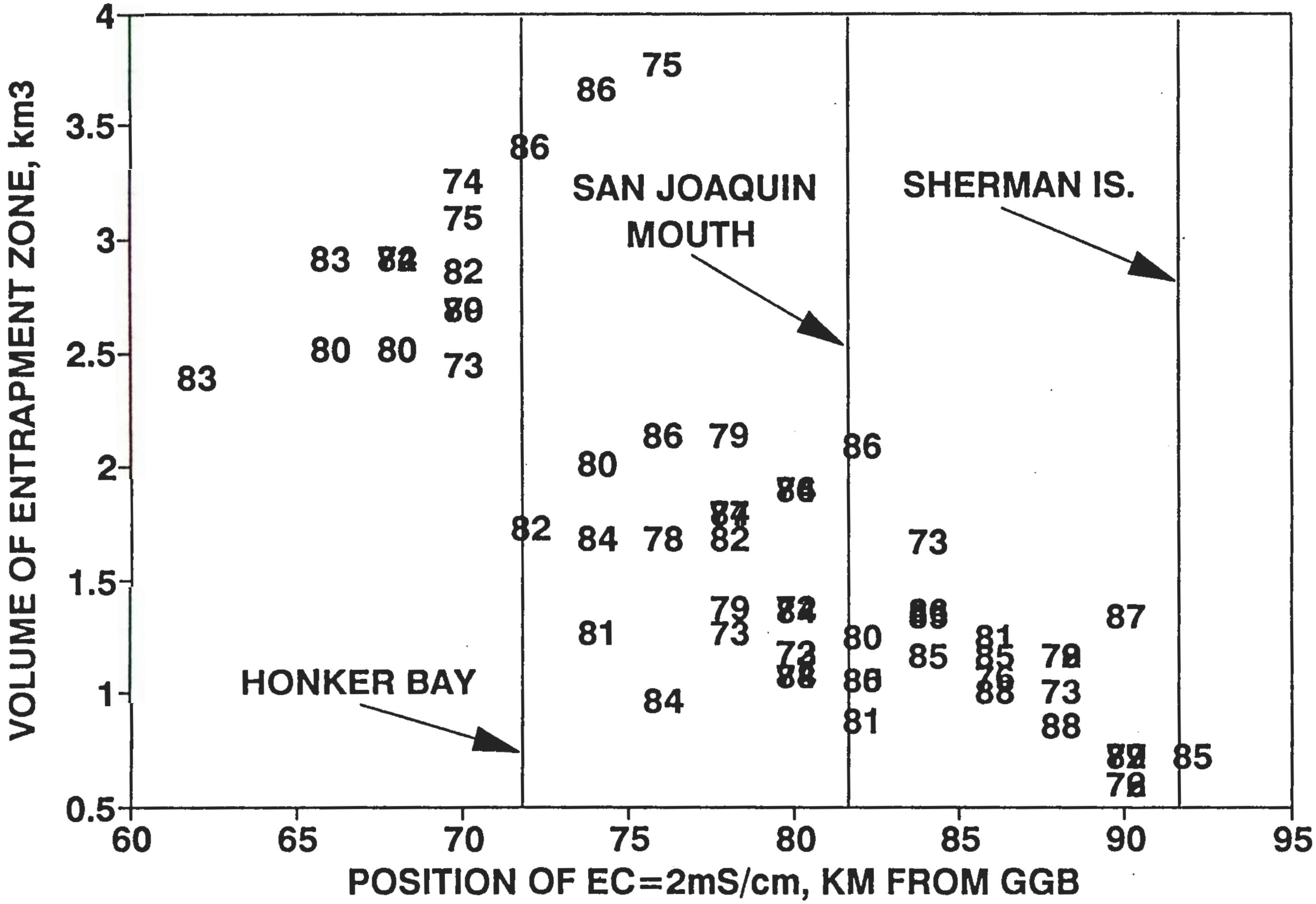


Figure 3. Volume of entrapment zone estimatted as volume between 2 and 10 mS/cm, vs. distance of 2 mS/cm from Golden Gate. Numbers are years.



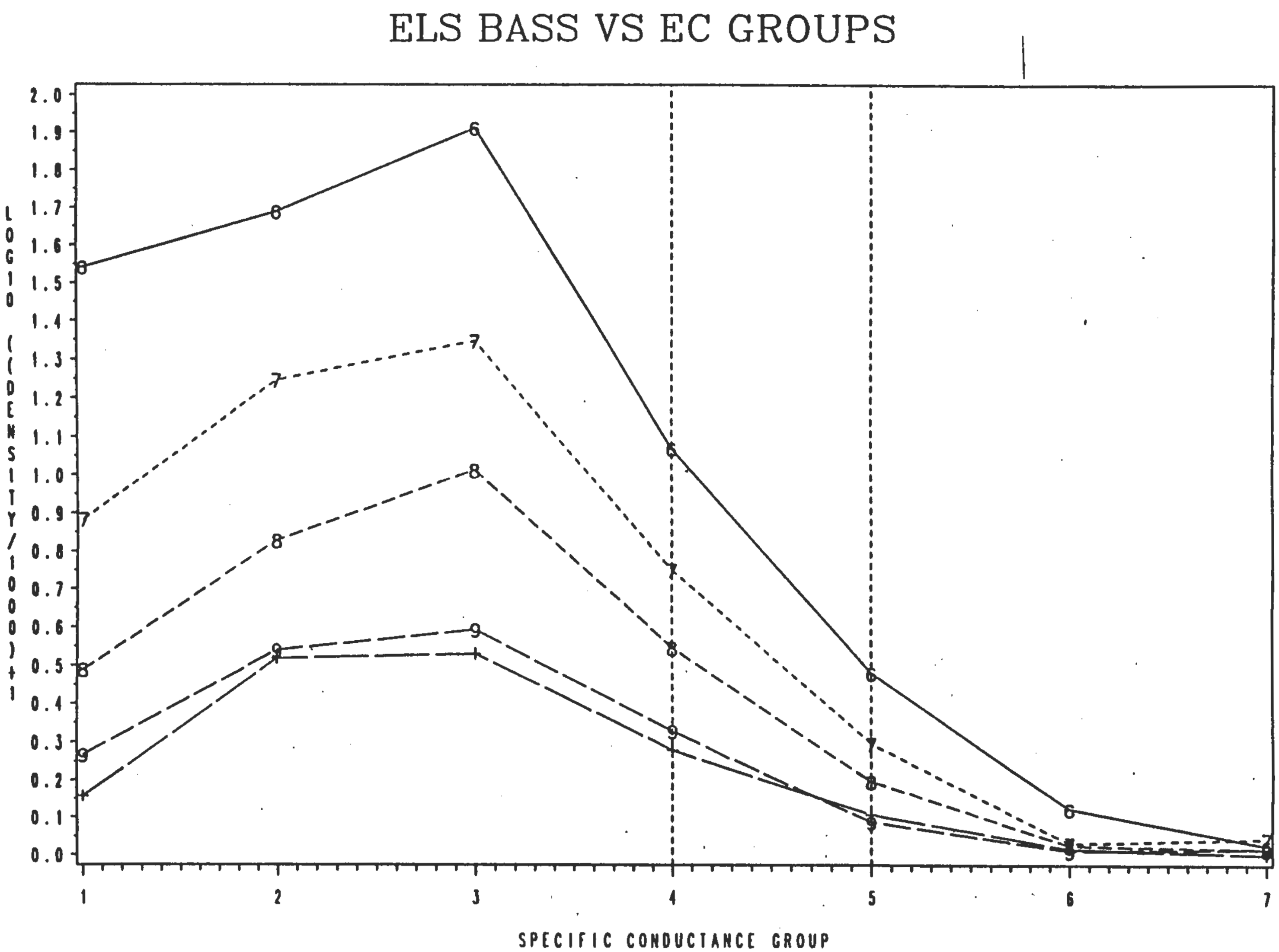


Figure 2a. The relationship between density of 6 mm to 14 mm striped bass and groupings of specific conductance (EC) for all samples made from April 12 through July 13 during the 1988 CDFG striped bass egg and larva survey in the Sacramento-San Joaquin Estuary. The vertical dotted lines encompass the EC range 1000 to 10000. The numbers indicate bass size. The plus indicates the combined 10mm-14mm densities.

AN ASSESSMENT OF THE ENTRAPMENT ZONE AND OTHER ESTUARINE SURROGATES FOR MANAGING FRESHWATER INFLOW TO THE SAN FRANCISCO BAY ESTUARY

Report of a Workshop
held at the
Bay Conference Center
Tiburon, California
27-29 August 1991

MARINE SCIENCES RESEARCH CENTER

STATE UNIVERSITY OF NEW YORK

AN ASSESSMENT OF THE ENTRAPMENT ZONE AND OTHER ESTUARINE SURROGATES FOR MANAGING FRESHWATER INFLOW TO THE SAN FRANCISCO BAY ESTUARY

Report of a Workshop
held at the
Bay Conference Center
Tiburon, California
27-29 August 1991

COAST Institute

of the

Marine Sciences Research Center

J.R. Schubel

Project Director

Special Report 94
Reference No. 91-13

Approved for Distribution

J. R. Schubel
Dean and Director

AN ASSESSMENT OF THE ENTRAPMENT ZONE AND OTHER ESTUARINE SURROGATES FOR MANAGING FRESHWATER INFLOW TO THE SAN FRANCISCO BAY ESTUARY

WORKSHOP PARTICIPANTS

Charles Armor
James Arthur
Douglas Ball
Randall Brown
Peter Chadwick
James Cloern
James Cowen
Michael Ford
David Fullerton
Charles Hanson
Susan Hatfield
Perry Herrgesell
Alan Jassby
David Jay
Jerry Johns
Wim Kimmerer
John Krautkraemer
B.J. Miller
Lee Miller
Steven Monismith
Peter Moyle
Frederic Nichols
David H. Peterson
Thomas Powell
Harry Seraydarian
Charles Simenstad
Lawrence Smith
Gregory Thomas
Philip Williams
Leo Winternitz

FACILITATOR

J.R. Schubel

RAPPORTEUR

Susan E. Schubel

INTRODUCTION

This report summarizes the principal conclusions and recommendations of a workshop held at the Bay Conference Center in Tiburon, California on 27-29 August 1991. The goals set for the workshop are stated in Exhibit 1.

EXHIBIT 1

PRE-WORKSHOP GOALS

- To critically review the current understanding of entrapment processes and phenomena in San Francisco Bay and to assess the importance of the entrapment zone (EZ) to the estuarine ecosystem. The workshop will examine how entrapment occurs, to what extent it occurs in a single, well-defined EZ, how various freshwater flow scenarios affect the position of the EZ and how EZ position affects biological components of the estuary. Participants will identify scientific areas of agreement and disagreement.

This assessment will provide the basis for pursuing the remainder of the goals -- the raison d'être of the workshop.

- To evaluate the scientific validity of using the position of the entrapment zone as a surrogate for managing freshwater inflow to protect the San Francisco Bay ecosystem and important societal values and uses.

- To identify and evaluate the scientific validity of other estuarine properties and phenomena as potential surrogates for managing freshwater inflows to protect the ecosystem and important societal values and uses of San Francisco Bay.

- To assess how the value of the position of the EZ and other surrogates for managing freshwater inflows to San Francisco Bay would be affected by other management and engineering actions.

The agenda for the workshop is included as Appendix A. The participants and their affiliations are listed in Appendix B.

White papers were prepared and distributed to workshop participants several weeks before the workshop. The papers summarized data and information relevant to the workshop so that meeting time at the workshop could be used more effectively. The titles and authors of the white papers are included in Appendix C. The papers are contained in a supplement to this report and are available upon request. Discussion of the issues identified in the white papers was the first important order of business for the workshop.

SUMMARY OF THE EVALUATION OF THE EZ AS A TOOL FOR MANAGING INFLOW TO THE BAY

Exhibit 2 summarizes the major points of agreement and conclusions of workshop participants on the use of the entrapment zone as a tool for managing freshwater inflow to San Francisco Bay. Exhibit 2 is based upon a facilitated discussion of the white papers by the workshop participants. The summary was presented at the workshop and all agreed that it was a comprehensive and accurate summary of the major conclusions they had reached.

EXHIBIT 2

CONCLUSIONS CONCERNING THE USE OF THE EZ AS A TOOL FOR MANAGING FRESHWATER INFLOW TO SAN FRANCISCO BAY

- The value of the position of the EZ as a tool for managing freshwater inflows may have been exaggerated because of the

  (1) Large uncertainty in understanding the importance of EZ position and EZ processes to sedimentation, to nutrient cycling, to contaminant cycling, to biology, etc. It's not only EZ position that counts, but also strength of the EZ.

  (2) Poor correlation between EZ position and important "values," e.g. success of year classes of striped bass.

  (3) Difficulty in measuring the position of the EZ precisely and accurately.

  (4) Existence in San Francisco Bay of multiple EZs of different kinds and causes.

- The terms entrapment zone, turbidity maximum and null zone are related, but are not synonymous.

- Measuring surface salinity is not the best way to establish the location of the EZ, the turbidity maximum or the null zone. Some measure of bottom salinity (combined with optical back scattering) would be better -- more diagnostic.

- There is significant scatter in the relationship of the position of the EZ to success of year classes of important species.

- The use of <u>surface</u> salinity to define the location of the EZ adds bias and ambiguity to apparent EZ position.

- A number of processes contribute to formation and maintenance of the EZ and, at certain times of the year there may be more than one EZ in San Francisco Bay.

- Although use of the EZ as a management tool may not be justified scientifically, there are advantages to using one, or more, estuarine properties and phenomena which respond clearly and unambiguously to freshwater inflow to manage freshwater inflow rather than relying entirely upon flow itself.

- The salinity distribution would be a better choice than the position of the EZ for this purpose.

It should be clear from Exhibit 2 that early in the workshop the participants rejected the EZ as the most appropriate response of the estuary to changes in freshwater inflow for use in managing inflow.

THE SEARCH FOR OTHER SURROGATES FOR MANAGING INFLOW

If a major purpose of setting discharge standards for the rivers that flow into San Francisco Bay is to conserve and, if appropriate, to restore important ecosystem functions and values and societal uses of the estuary, then the best "measures," upon which standards should be set are a combination of freshwater inflow and some response of the estuary to that input.

It is extremely desirable to add a second standard; one that measures the response of the estuary to the input of freshwater from Delta outflow. The ideal index for that standard is an index that is simple to measure, inexpensive to measure, one that can be measured accurately, one that has ecological significance, one that integrates a number of important estuarine properties and processes and one that is meaningful to a large number of contituencies.

The workshop examined a number of surrogates for managing freshwater inflow. The one which received the greatest attention was near-bottom salinity. Salinity was judged to be a better -- a more desirable and diagnostic measure -- than the EZ and, indeed, was judged to be the best measure for an estuarine standard for flows identified by workshop participants. The major advantages of salinity as a measure are summarized in Exhibit 3.

EXHIBIT 3

PRIMARY REASONS FOR SELECTING SALINITY AS THE MEASURE FOR CREATING A STANDARD FOR MANAGING FRESHWATER INFLOWS

(1) The salinity distribution is of fundamental importance to the ecosystem.

(2) The salinity distribution is a result of the interplay of freshwater inflow, geometry of the basin, diversion in the delta and tidal regime.

(3) Accurate measurement of salinity is direct, easy and economical; measurements are robust.

To clarify the advantages and disadvantages of the use of salinity as the basis for a flow standard, workshop participants engaged in an exercise of Six Hats Thinking as described by Edward DeBono. The strategy is designed to clarify thinking and analysis of complex issues, issues which often are emotionally charged. The use of salinity, or of any other property, as a surrogate for direct measurement of river inflow in managing inflow to the estuary meets these criteria. In six hats thinking, each of six colors is assigned to a particular mode of thinking (Exhibit 4), and only that mode of thinking is permitted while wearing a hat of that particular color. The procedure calls for the facilitator to orchestrate an appropriate sequence of the six modes of thinking by directing switching of hats at critical points in the discussion. All individuals in the group must wear hats of the same color at the same time.

The results of the six hats thinking session are summarized in Exhibits 5 through 8. The white hat was not used because much of the day had already been devoted to an enumeration and discussion of the "facts." The facilitator provided the blue hat thinking and the results are incorporated into the text.

EXHIBIT 4

SIX HATS THINKING

THE MEANING OF THE SIX COLORS

<u>White</u>:	Like Joe Friday on "Dragnet" used to say: "Just the facts, Mam." Facts, figures, data, information, questioning, defining the need for information, neutral, objective.
<u>Black</u>:	Negative, everything bad; but objections must have a logical basis.
<u>Yellow</u>:	The flip-side of black. Advantages, opportunities, benefits. Everything good; but arguments must have a logical basis.
<u>Red</u>:	The emotional reaction; NO reasons required. Feelings, hunches, insight, emotion, anxiety, doubt.
<u>Blue</u>:	Conductor of the orchestra. The balance; the over-view; consideration of the subject at hand <u>plus</u> the thinking process itself, procedures, NOT substance. Should we reach a consensus? Do we need a new agenda?
<u>Green</u>:	Creativity, generation, proposals, alternatives, suggestions. Reasons are <u>not</u> required; no value judgements are permitted.

EXHIBIT 5

THE GOOD POINTS OF SALINITY AS A SURROGATE FOR FRESHWATER INFLOW

YELLOW HAT THINKING

- Salinity has biological significance.
- Salinity is understandable by the public.
- Salinity is easy and inexpensive to measure.
- Salinity is a conservative property; it's easy to model.
- Salinity integrates river flow and diversion.
- Salinity accounts for physical changes in the system.
- Salinity compensates for errors in flow measurements.
- There is an established historical salinity record for comparison.
- Salinity is a measure of habitat.
- Salinity is important to endemic species.
- A salinity standard would protect against salt water intrusion into freshwater intakes.
- Salinity is an index to the location of the turbidity maximum.
- Salinity is an index to the location of the EZ.
- Salinity is a guide to the density gradient which has dynamic significance.
- There is a precedent for salinity standards.
- One can infer the general circulation and mixing patterns from the salinity field.
- Salinity is useful in evaluating proposed dredging projects.
- The use of salinity as a standard will encourage EPA involvement in managing freshwater inflows.

EXHIBIT 6

THE BAD POINTS OF SALINITY AS A SURROGATE FOR FRESHWATER INFLOWS

BLACK HAT THINKING

- A salinity standard would be harder for management to operate than would delta outflow.
- Salinity simplifies a set of complex phenomena.
- A salinity standard would be difficult to manage to because of confounding effects of tides and climatology.
- Salinity depends upon evapotranspiration which is poorly known.
- Variability of salinity in the coastal ocean is poorly known.
- Most biological data in the estuary are correllated with flow, not salinity.
- Salinity covers up ignorance.
- The use of salinity will pose additional cost to the State.
- The ecological significance of salinity is not well defined.
- Confusion on historial significance of salt intrusion in bay.
- The use of salinity may lead to unachievable flow standards.
- Salinity confuses direct toxic effects of salt with flow-correlated effects.
- There are sources of salt to the estuary in addition to the ocean.
- The use of salinity would decouple cause-effect relationships.
- A salinity standard would be non-mechanistic.
- The benefits associated with a particular salinity are difficult to quantify.
- Increased inflow does not guarantee strong year classes of fish.
- A salinity standard could encourage construction projects (dams, diversion canals).
- A salinity standard may facilitate EPA getting involved in the decision making process in San Francisco Bay.

EXHIBIT 7

THE EMOTIONAL REACTIONS TO A POSSIBLE SALINITY STANDARD

RED HAT THINKING

- It might increase taxes.
- At least one participant expressed concern about the risk of the workshop prescribing too much.
- Another participant expressed concern that the workshop would not prescribe enough.
- People are ignoring the values.
- At what level are we protecting resources? Are we protecting fish or alfalfa?
- Need a tool to couple cause and effect; salinity doesn't do it.
- The San Francisco estuary needs goals - - not just numbers. What values and uses of the estuary are we striving for?
- Frustration: There already <u>are</u> standards. Why don't we enforce them? What scientific evidence do we have for these?
- A salinity standard has little relationship to the aesthetic appeal of the estuary; e.g. fish that smell like cucumbers.
- We do have historic records.
- An expression of elation at progress made in the workshop, but worry about the uncertainty that lingers.
- Let's get moving with what we have.
- There are good fisheries-flow data; they should be used. A salinity standard would decrease their management value.

EXHIBIT 8

THE CREATIVE APPROACH TO USING SALINITY AS A SURROGATE FOR FRESHWATER INFLOW

GREEN HAT THINKING

- It's difficult to set diagnostic standards if we don't know what we want to achieve. Start by stating goals and objectives, probably in terms of desired values and uses of the system.
- Make the best possible statements re: level of certainty associated with the proposed salinity standard and each issue.
- Management sets a high priority on certainty. Should we advise this?
- An assessment of existing standards needs to be done; an assessment of the consequences of remaining where we are. What will happen to the estuary and its living resources if present management policies and practices continue?
- Because of the level of uncertainty we need research and monitoring programs to track the environmental consequences of whatever decisions are made if we are to improve decision making in the future.
- We need to identify what <u>isn't</u> being done now that should be and do it. Enforce existing standards.
- The world is likely to remain uncertain; there are no permanent decisions, only interim decisions.
- We need a scale of uncertainty relative to other systems.
- There is information on physical processes in EZ available from the UK and other places; it should be exploited.
- We need a conceptual framework of how components of the EZ fit together -- biological relationships to physical processes.
- Don't ignore the value of using adaptive management to test hypotheses and conceptual models.

THE RECOMMENDED APPROACH

Following the six hats thinking exercise, there was further discussion of the use of salinity as the basis for a standard for managing delta outflow to protect important estuarine values and uses and living resources. The conclusions and recommendations are summarized in Exhibit 9. All were agreed to by the workshop participants.

The workshop concluded that a combination of measures associated with freshwater inflow are needed to develop standards to ensure the required levels of protection for the estuary and its living resources. The minimum combination is river inflow and near-bottom salinity. Salinity should be thought of as a complement to measuring inflow. Reliable direct measurements of delta outflow would have great benefit to managers and scientists and the USGS program should move from the research and development phase to the monitoring phase as soon as practicable. Until then, the combination of river inflow, diversion and near-bottom salinity are the most appropriate set of measures. It represents the response of the estuary to different combinations of river inflow, diversions and withdrawals, tidal climatology and basin geometry.

A position of the 2 ‰ near-bottom isohaline should be selected for each season which provides an appropriate level of ecosystem protection. These positions should become seasonal standards. They should be viewed as upstream limits of the excursions of the 2 ‰ isohaline needed to provide the minimum level of environmental protection given the present level of scientific uncertainty. The proposed strategy for managing Delta outflow is to fix the upstream position of the near-bottom 2 ‰ isohaline during different seasons using the best scientific evidence available to protect important ecosystem values and uses. The upstream position would vary from season to season and the downstream position of the 2 ‰ isohaline would be unconstrained. There are different levels of scientific certainty/uncertainty associated with these positions for different species/values/uses for different seasons. Because of the uncertainty, the positions are somewhat elastic. From the environmental perspective, the uncertainty dictates taking a conservative approach, i.e. pushing the 2 ‰ isohaline farther downstream than might be required with more information.

These seasonal standards should not be interpreted as static targets for location of the 2 ‰ isohaline throughout any given season, year after year. Variability in flow, in circulation and mixing, in the salinity distribution and in the distribution of other important properties and processes is important in maintaining a healthy estuarine ecosystem.

The biological importance of seasonal and interannual variability and of extreme stochastic events should not be underestimated. For example, very successful year classes of striped bass are always, or almost always, associated with high inflow, but not all high flow years produce strong year classes. During years when there are extraordinarily strong year classes, the striped bass occupy an extended area (and volume) of the system. This has been demonstrated in a number of estuarine systems including: San Francisco Bay, the Hudson River estuary, Chesapeake Bay and the Santee-Cooper estuary. In the Hudson River system (NY), for example, very strong year classes of striped bass are associated with large riverflows which push the EZ well downstream spilling freshwater out of the channel and onto extensive shoal areas that border the channel. Suisun Bay may be the San Francisco Bay estuary analog of the New York situation.

The positions prescribed for the near-bottom 2 ‰ isohaline would be for operation of the existing State and Federal water diversion and distribution system. Any proposed change in that system should trigger a reevaluation of the positions. The movement of the 2 ‰ isohaline to the prescribed position would be achieved through some combination of adjustments in river inflow and diversion.

Scientists at the workshop not only felt comfortable in advocating the position of 2 ‰ near-bottom isohaline as the basis for the proposed management strategy, but were enthusiastic about it. They were not comfortable, however, in prescribing specific positions (i.e. specific salinity standards) during the workshop. All believed that this required the analysis and interpretation of data and information which were not available at the workshop and considerably more time for a critical and thoughtful assessment. Discussion turned to developing a strategy for selecting the most appropriate position of the 2 ‰ isohaline for each season.

Table 1 is an attempt to relate the strength of the coupling of outflow, delta diversion and EZ processes to the success of a variety of species. A selected group of species representing the broad range of organisms found in the San Francisco Bay estuary was rated as to what effect delta outflow, diversions and entrapment zone processes had on the importance of determining a strong year class of each species.

The rating system consisted of +1, 0, -1 and U. Plus one (+1) denotes a reasonable degree of confidence among workshop participants that a positive relationship exists between the particular variable and species year class strength. Negative one (-1) denotes a reasonable degree of confidence that a negative relationship exists. Zero (0) denotes reasonable certainty that no relationship exists. "U" denotes that participants are uncertain if any relationship exists.

Certainty or confidence is based on relationships of abundances to outflow and/or diversion and on the combined best professional judgement of the working group of fishery biologists at the workshop. They drew upon their collective knowledge of species biology and numerous studies both in the San Francisco Bay estuary and in other estuarine systems.

EXHIBIT 9

SALINITY AS A BASIS FOR A STANDARD IN MANAGING FRESHWATER INFLOW

- Salinity should be measured at 1m above the bottom.
- The position of the 2 ‰ isohaline at +1m is recommended for use as an interim standard. (Note: the leading edge of the turbidity maximum is located at about 2 ‰).
- Salinity should be measured at six stations located along the channel between Emmaton and Carquinez Bridge.
- Optical backscatterer sensors should be combined with conductivity probes at these stations.
- Surface salinity should also be monitored at these stations and correlated with bottom salinity.
- The data should be telemetered to a convenient location for timely analysis and interpretation.
- The monitoring data should be supplemented with detailed salinity surveys to map the distribution of salinity in three dimensions.
- The salinity standard should take the form of the position of the 2 ‰ isohaline in near-bottom (+1m) channel waters as a function of season.

TABLE 1

Summary of best professional judgement of workshop participants of the relationship of success of different species with outflow, delta diversion and EZ processes. +1 indicates reasonable confidence in a positive relationship; -1 indicates reasonable confidence in a negative relationship; 0 indicates reasonable confidence that no relationship exists and U indicates the level of uncertainty is too high to make a judgement.

Species	Outflow	Delta Diversion	EZ Processes-recruitme
Sturgeon	+1	0	U
Longfin smelt	+1	U	+1
C. Franciscorum	+1	0	U
Starry Flounder	+1	0	0
Delta Smelt	U	-1	U
Splittail	+1	U	0
Striped Bass	+1	-1	0
American Shad	+1	-1	0
Salmon	+1	-1	0
Neomysis	+1	U	+1
Eurytemora	U	0	+1
Anchovy and Marine Species	0	0	0
Palaemon m.	0	0	U
White catfish	0	-1	0
Largemouth Bass	0	0	0
Primary organic carbon food supply	+1	-1	+1

For chinook salmon there is a positive relationship with outflow for San Joaquin River stocks, but Sacramento River stocks there was some uncertainty as to if a positive relationship exists.

For both salmon and American shad inflow to the delta may be a better variable than delta outflow.

Primary food sources consist of organic carbon input plus phytoplankton.

The strategy developed for selecting the most appropriate position of the 2 ‰ isohaline was to array all relevant information in a matrix similar to that shown in Exhibit 10. This matrix was developed and applied at the workshop for the spring season for the San Francisco Bay estuary. The actual data are not included in this report. Their omission is intentional. The matrix data was developed over a period of less than two days without access to published data or information. The only sources available were the memory banks of the assembled experts. While the participants have confidence in the merits of the approach, many were reluctant to have the data printed because of the ways in which they were generated and the potential for casting an unreasonable degree of authority over them.

A matrix is a useful way of summarizing a large number and diverse variety of complex estuarine responses to fluctuations in freshwater inflow and the accompanying changes in the salinity distribution driven by those fluctuations. A matrix is not however, a powerful or persuasive tool for packaging that information either for decision makers responsible for setting and enforcing freshwater or salinity standards, or by the public in understanding the scientific basis for those standards.

The workshop participants developed a new tool for those purposes. It is a graphical tool which summarizes diagnostic environmental information for critical species -- species which if protected will provide protection for other important species, ecosystem values and functions -- in clear, concise and compelling ways. The curves are easy to understand and difficult to ignore. An illustrative example of such a curve is shown in Exhibit 11.

Exhibit 11 is an illustrative sketch of the normalized probability of a strong year class of a key species plotted against the distance downstream of the near-bottom 2 ‰ isohaline. The lower curves represent the level of uncertainty associated with the estimates. The figure indicates that within the zone extending from the origin to X_1, the slope of the curve is nearly flat, indicating that the probability of a strong year class changes little within this region of the system. This zone might correspond to the region of the delta where displacement of the 2 ‰ isohaline farther seaward yields relatively little ecological benefit because of the controlling influence of entrainment losses. Seaward of this zone from X_1 to X_2, the probability of a strong year class increases relatively rapidly with increased displacement of the 2 ‰ downstream. Seaward of X_2, the rate of increase again flatters out and displacement of the 2 ‰ isohaline beyond some limit may actually decrease the probability of a strong year class.

The proposal is to construct a series of such curves for appropriate life history stages of key species of the San Francisco Bay-Delta estuary and to aggregate them by season. The next step is to use the family of curves for each season to select a position of the near-bottom 2 ‰ isohaline that would provide an appropriate level of ecological protection for the sum of these species, and presumably for protection of the estuary, that is based upon the best scientific evidence available. The position of the near-bottom 2 ‰ isohaline selected for each season would be the salinity